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ON THE HYPOTHESIS OF ISOSTASY

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The splendid papers by Hayford[1] and jointly by Hayford and Bowie[2] have brought the subject of isostasy into the foreground for discussion by geologists and others who may be interested. These papers have taken the subject out of a field of more or less vague conjecture, and by subjecting it to a very careful quantitative examination have shown very clearly that isostasy in some form can be accepted as a reality.

To be sure, they have not *proved* the reality of isostasy, for in the mathematical sense no physical hypothesis can be proven. But they have formulated precise hypotheses of isostasy and have shown that a vast mass of observational data covering the United States is very much better satisfied by theories which include their hypotheses than by the usual gravitational theory which excludes the hypothesis of isostasy.

Four distinct laws of isostasy have been discussed in these papers, viz., (*a*) uniform compensation, (*b*) uniformly decreasing

[1] John F. Hayford, *The Figure of the Earth and Isostasy from Measurements in the United States*, Publications of the U.S. Coast and Geodetic Survey, 1909.

[2] John F. Hayford and William Bowie, *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, Publications of the U.S. Coast and Geodetic Survey, 1912.

compensation, (*c*) compensation in a subterranean layer, (*d*) the Chamberlin compensation. In so far as merely satisfying the observations it is found that any one of these hypotheses is as good as any other, since each of them reduces the sum of the squares of the residuals by about 90 per cent. This is a very notable reduction and it places the hypothesis of isostasy upon a solid foundation of credibility. We say "credibility" and not "proof" advisedly, for there still remains the possibility that some other hypothesis, non-isostatic in its nature, may satisfy the observations even more closely, and it is a very difficult matter to show that no such hypotheses exist.

There seems to be nothing inherently improbable in the notion that the density of the materials under the continents is less than that under the oceans. Hayford's success, which must be considered a notable one, consists in showing, by very complete computations which extend over a large mass of data, that assumptions of very moderate differences of density are sufficient to bring the observations and theory into fairly close accord. Whether or not any other hypothesis will or can be equally successful must of course be left for the future. Until some such hypothesis makes its appearance we are fairly entitled to put our faith in the broader outlines of isostasy and leave it to further observations and discussions to make the details of the theory more precise.

Notwithstanding the fact that all four of the hypotheses discussed by Hayford satisfy the observations equally well, it would seem as if Hayford prefers the hypothesis of uniform compensation to a depth of 122 kilometers and usually has this hypothesis in mind when thinking of isostasy. This preference, which does not seem to be warranted by his own discussions,[1] is somewhat dangerous in that conclusions which are peculiar to this hypothesis are given a prominence to which they are not entitled. Thus, one is

[1] Second, it is not possible to ascertain whether this compensation is more probable than the G compensation, uniformly distributed from the surface to the depth 70.67 miles, since the two sets of computed deflections agree so closely that their differences are much smaller than the accidental errors.—*The Figure of the Earth and Isostasy from Measurements in the United States*, p. 159.

A corresponding statement is made on p. 162 with respect to the Chamberlin compensation.

rather likely to gain the impression from Hayford's writings that the "depth of compensation" is in the neighborhood of 122 kilometers and that this "depth" is as well established as are the broader outlines of the theory. This is not true, for we do not know that the compensation is uniform. From the hypothesis of uniformly decreasing compensation Hayford finds the depth of compensation to be 175 kilometers, and from the "Chamberlin compensation" 286 kilometers. Clearly, the "depth of compensation" is very sensitive to change of hypothesis, and it is further clear that with a slight modification of the hypothesis the "depth of compensation" could be made to retreat to the center of the earth, or even to vanish altogether.[1] From this it is obvious that the existence of a precise depth of compensation is not an essential part of the theory of isostasy. These considerations deprive the depth of 122 kilometers of the importance or weight which constant repetition is likely to attach to it. It is still doubtful whether the term "depth of compensation" corresponds to any physical reality, however useful the idea may be in our hypotheses.

If the solid portion of the earth were altogether lacking in rigidity, and if the concentric layers were homogeneous in density, then the upper surface of the solid earth would be an oblate spheroid, and this surface would lie about 9,000 feet below the present sea-level. It would be covered uniformly by the waters of the ocean, and the pressure at any interior point would be a function of latitude and depth only, and not a function of the longitude. Let us suppose now that this solid spheroid is endowed with a certain amount of rigidity and is differentiated somewhat with respect to density, particularly in the neighborhood of the surface. If the rigidity were not too great, it seems clear that the heavy regions would be depressed by the excessive weight, and that the lighter regions would rise on account of their deficiency of weight. If the differentiation of density were sufficiently great, it is clear that the

[1] The idea implied in this definition of the phrase "depth of compensation" that the isostatic compensation is complete within some depth much less than the radius of the earth is not ordinarily expressed in the literature of the subject, but it is an idea which is difficult to avoid if the subject is studied carefully from any point of view.—Hayford and Bowie, *The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity*, p. 10.

regions of sufficiently deficient density would eventually appear above the surface of the waters of the ocean, while the regions of greatest density would form the great depths of the basins into which the the waters of the ocean were gathered. Those regions which have neither excess nor deficiency of density would still remain about 9,000 feet below the sea-level except in so far as, through rigidity, they partook of the movement of neighboring regions. A theory of isostasy comprehending the entire earth in its grasp should therefore be based upon a level 9,000 feet below the surface of the ocean. Regions which lie above this level are deficient in density and regions which lie below this level are excessive in density. Clearly, it would not do to regard the sea-level, which from an isostatic point of view is an accidental level, as the dividing surface. Indeed, if the differentiation of density were so small that the elevated regions were all below the sea-level, we should be compelled to conclude that the density was everywhere excessive—a *reductio ad absurdum*.

But the sea-level is precisely the surface which Hayford has chosen, and, as a consequence, to all those regions which lie between the sea-level and 9,000 feet thereunder he has ascribed an excess of density instead of a deficiency. Since approximately three-quarters of the earth's surface lies under the ocean at an average depth of approximately 15,000 feet, and since under Hayford's hypotheses too great density is ascribed to this region, it would seem that his hypothesis has had the effect of raising the mean surface density for the entire earth from 2.67 to a somewhat higher figure. This alone might not be of any great importance, since at best the figure 2.67 is somewhat uncertain, but a hypothesis which is based upon sea-level gives horizontal changes of defect of density over the continents which are relatively too great, as is shown in Table I, which is based upon the hypothesis of uniform compensation.

Thus, with the sea-level basis the defect in density under a region which has an altitude of 6,000 feet is six times as great as the defect in density under a region which has an elevation of 1,000 feet, while with a true, isostatic theory the defect would be only one and one-half times as much. The defect under a 1,000-foot

elevation is twice as great as under a 500-foot elevation on the one hypothesis and only twenty-nineteenths times as great on the other. This indicates that the sea-level basis overaccentuates the importance of changes of level in the topography of the continents.

TABLE I

Elevation in Feet	Defect in Density Sea-Level Basis	Defect in Density 9,000-Foot Basis	Elevation in Feet	Defect in Density Sea-Level Basis	Defect in Density 9,000-Foot Basis
0.....	0	9	4,000.....	4	13
1,000.....	1	10	5,000.....	5	14
2,000.....	2	11	6,000.....	6	15
3,000.....	3	12	7,000.....	7	16

If the density in the earth's crust actually varies in the manner supposed by Hayford (using the sea-level basis), one would expect regions over which the compensation was effected to be smaller than if the density varies according to a true isostasy (i.e., the 9,000-feet-below-the-sea basis), since the changes in density are relatively greater in the first case than in the second. Hayford has attempted to determine the sizes of these areas of compensation, but the quantities to be considered were so small that success was scarcely to be expected; indeed, they are "frequently less than the errors of observation and computation" and, possibly, also less than the effects of local irregularities of density. The evidence, though inconclusive, leaned faintly toward rather small areas of compensation, and Hayford is of the opinion that these areas are between a square mile and a square degree.[1] If the present writer is correct in assuming that a true isostasy must be based upon a level 9,000 feet below the sea, then the evidence published by

[1] It is certain from the results of this investigation that the continent as a whole is closely compensated, and that areas as large as states are also closely compensated. It is the writer's belief that each area as large as one square degree is generally largely compensated. The writer predicts that future investigations will show that the maximum horizontal extent which a topographic feature may have and still escape compensation is between one square mile and one square degree. This prediction is based, in part, upon a consideration of the mechanics of the problem.—Hayford and Bowie, *The Effects of Topography and Isostatic Compensation upon the Intensity of Gravity*, p. 102.

Hayford and Bowie on the extremely delicate question[1] of the "areas of compensation" is not altogether trustworthy, and the sizes of these areas must be regarded as unknown.

From the fact that the hypothesis of isostasy reduced the sum of the residuals from 65,434 to 8,013, or by approximately 90 per cent, and from the fact that the average elevation of the United States is about 2,500 feet Hayford concluded that the average departure from complete isostasy in the United States is equal to about 250 feet of rocks. It is not easy to see how Hayford drew this conclusion. It certainly has no mathematical justification, for even if the theory were perfect and the isostasy complete, the sum of the squares of the residuals would not be zero, since the imperfections of the observations would still give us a very respectable, but quite unknown, sum. How then can we form a quanti-

[1] If the separate anomalies in the United States be compared, it is found that in 16 cases out of 41 the anomaly with local compensation assumed is smaller than with regional compensation assumed uniformly distributed to zone K (18.8 kilometers), and only 13 cases in which it is larger. Similarly, there are 20 cases out of 41 in which the anomaly with local compensation is smaller than with regional compensation extending to zone M (58.8 kilometers), and only 15 cases in which it is larger. There are 26 cases out of 41 in which the anomaly with local compensation assumed is smaller than with regional compensation assumed to extend to zone O (166.7 kilometers), and only 12 cases in which it is larger. In all other cases the two anomalies compared are identical to the last decimal place used, the third.

The evidence either for or against local compensation in comparison with such regional compensation distributed uniformly over these moderate distances is necessarily slight and possibly inconclusive. For, as shown in the table, the difference between computed effects of compensation in the two cases compared is very small upon an average. The whole evidence is furnished by these very small differences, which frequently are less than the errors of observation and computation. As shown by the table, there is but one station among the 41—namely, No. 43, Pike's Peak—at which the difference between the computed effect of local compensation and the computed effect of regional compensation uniformly distributed to zone K exceeds 0.004. Such a difference tends to become greater as the distance over which the regional compensation is supposed to be uniformly distributed is increased, but columns 7 and 8 of the table show that even when the regional compensation is assumed to extend to zone O, a distance of 166.7 kilometers, from the station, there is only one station among the 41—namely, station no. 54, San Francisco—at which the computed effect of local compensation and the computed effect of regional compensation exceeds 0.017 dyne.

Nevertheless the evidence, slight as it necessarily is, indicates that the assumption of local compensation is nearer the truth than the assumption of regional compensation uniformly distributed to zone K (18.8 kilometers). The evidence is still stronger in the same direction when the comparison is made between local compensation and regional compensation extending uniformly to the greater distances, 58.8 and 166.7 kilometers, represented by zones M and O.—Hayford and Bowie, *The Effects of Topography and Isostatic Compensation upon the Intensity of Gravity*, p. 101.

tative judgment from the sum of the squares of the residuals which depends, not only upon the imperfections of the theory, but upon the imperfections of the observations as well? Obviously, it cannot be done. The estimate of 250 feet is little more than a guess, however shrewd the guess may be. If we use the 9,000-foot level as the basis of our guess, then the average elevation of the United States is 11,500 feet, and the average departure from complete isostasy is 1,150 feet of rocks instead of 250 feet. It would not be altogether fair, however, to make this direct substitution, for the reduction of the sum of the squares of the residuals from 65,434 to 8,013 was accomplished on the sea-level hypothesis, and the reduction might be quite different under another hypothesis.

From a purely mathematical point of view, any set of a finite number of observations of the intensity and direction of gravity can be satisfied, not approximately, but exactly, in infinitely many ways by a proper distribution of density in the earth. The virtue of the theory of isostasy, therefore, lies, not in the mere fact that the observations are more nearly satisfied by the theory than without it, but in the fact that a definite principle is laid down for the variations of density, and that this principle brings theory and observations into a satisfactory accord. As Hayford's four distinct hypotheses show, any smoothly uniform hypothesis of isostasy can be regarded only as a first approximation to the actual situation, and Hayford has been successful in showing that any one of these four hypotheses is a good first approximation. It is equally clear that such delicate points as "depth of compensation" and size of "areas of compensation" depend for their successful determination upon the vastly more difficult matter of second and higher approximations, and these approximations can be obtained, if at all, only by a very much more dense net of observations, and quite likely the observations themselves would have to be still further refined.

While the theory of isostasy has made a very successful approach to the solution of the problem of bringing the anomalies of observation into accord with the theory of gravity, it must be admitted that there is no evidence to show that the solution of the problem is necessarily isostatic.

THE MIDDLE PALEOZOIC STRATIGRAPHY OF THE CENTRAL ROCKY MOUNTAIN REGION[1]

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[1] An abridgment of a thesis presented for the degree of Doctor of Philosophy at the University of Chicago, 1916.

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PART I

FOREWORD

This paper is the result of three months' field work by the writer in the central Rocky Mountain region during the summer of 1915, under the auspices of the University of Chicago. For assistance in planning the field investigation the writer is indebted to Dr. Eliot Blackwelder, of the University of Wisconsin, and to Dr. R. D. Salisbury, of the University of Chicago; for aid in the identification of fossils, to Dr. Stuart Weller, of the University of Chicago; and for helpful suggestions and criticism of the material of the thesis, to all of these gentlemen.

The problem centered about several broad gaps in the existing knowledge of the Ordovician, Silurian, and Devonian history of western Wyoming and adjacent parts of neighboring states; for example: (1) the "Jefferson limestone" of the Absaroka Range, of Yellowstone National Park, and of southwestern Montana was known to be in part Devonian, but the presence of Ordovician and Silurian strata within this formation and its relation to the Bighorn dolomite of central and north-central Wyoming were matters of dispute; (2) hiatuses were suspected at the base and at the top of the Ordovician-to-Devonian sequence of this region, and at more than one horizon within that sequence, but no physical evidence of any such hiatus ever had been cited; (3) the relation of the Wyoming Ordovician and Upper Cambrian to the corresponding systems in northeastern Utah had never been studied by careful stratigraphic comparison; and (4) the relation of the Silurian to the Ordovician in northeastern Utah was unknown.

By first-hand studies, in one season, of ten complete, and in most cases excellently exposed, sections at strategic localities scattered throughout the area involved, the writer is enabled to throw considerable new light upon all of these questions.

Because of the well-known scarcity of fossils in the strata which were to form the subject of his investigation, the writer set out with intent to make the greatest possible use of correlation by means of lithologic characters. To this end he made accurate measurements and described in detail, in every section, each member of the sequence which could be distinguished from other members by its lithological characters. Collections of fossils, although made secondary to the work of lithological description and measurement, and in no case exhaustive, were made wherever opportunity presented itself, and in each case served to corroborate the correlation which otherwise would have been made on the basis of lithology alone. For instance, the presence of the Ordovician Bighorn dolomite as the thick basal member of the so-called "Jefferson limestone" in the areas of the Absaroka, Wyoming (No. 52), and Livingston, Montana (No. 1), folios was established beyond doubt by both lines of evidence, though it would have been well established by either one alone.

In these correlations it was realized that the coincidence of the lithological characters of a single member at one locality with those of one member in the same stratigraphic position in another locality is much more inconclusive (although significant) than the correspondence of several successive members in one section to the same number of members occurring in the same order and in the same stratigraphic position in another. In nearly every case where a single bed in one section was found to correspond accurately in character to one bed in another section, not less than two other contiguous members were found to correspond in like manner. Where several members of one section appeared to be missing from another section, a hiatus was inferred in the latter; and such inference was substantiated in several cases by more direct evidence at the suspected horizon.

LOCATIONS OF SECTIONS MEASURED, 1915

(See map, Fig. 1)

I. (Partial.) In the northwest wall of the canyon of Big Goose Creek, about 20 miles southwest of Sheridan, Wyoming.

II. *Goose Creek Ridge.*—On the crest of the "limestone front ridge" on the northeast flank of the Bighorn Range, between Big and Little Goose creeks, about 20 miles southwest of Sheridan, Wyoming.

III. *Cody, Rattlesnake Mountain.*—On the southwest angle of Rattlesnake Mountain, north of Shoshone Dam, 9 miles west of Cody, Wyoming.

IV. *Dead Indian Creek.*—On the nose of the main ridge running parallel to the valley of Dead Indian Creek on the southeast side thereof, just south-

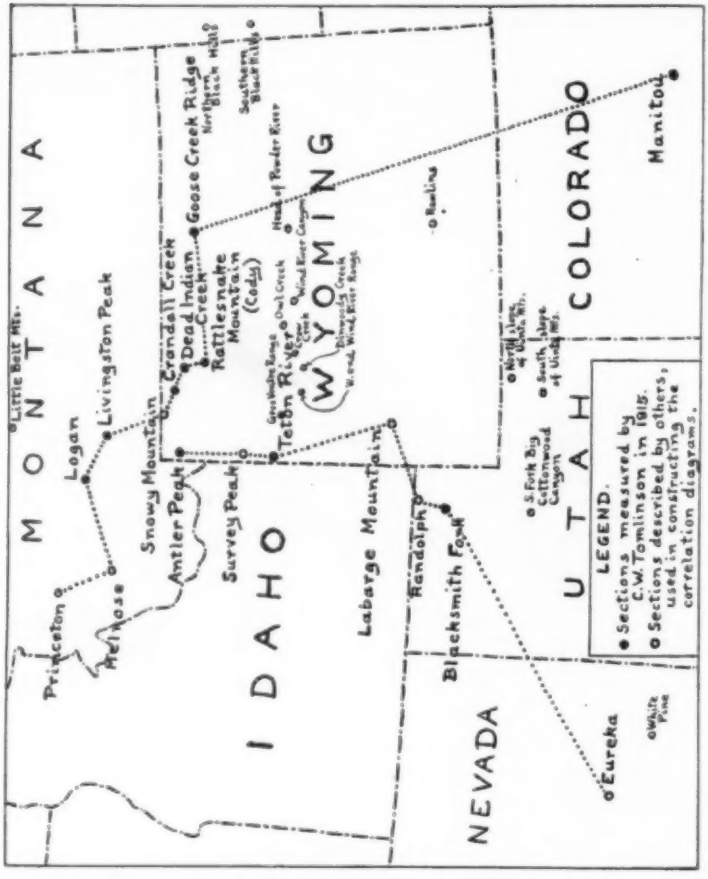

FIG. 1.—Map showing localities referred to in this paper

west of the crossing of the road from Cody to Sunlight Basin, Wyoming, a few miles east of the east border of the Crandall quadrangle.

V. *Crandall Creek.*—At the west end of the north slope of Windy Mountain, in the south wall of the valley of Clark Fork, near the mouth of Crandall Creek, in the Crandall quadrangle (Absaroka Folio), Wyoming.

VI. (Incomplete.) *Antler Peak*, Gallatin Range, Yellowstone Park, Wyoming.

VII. (Cambrian only.) On the ridge running west from the summit of Livingston Peak, Livingston quadrangle, Montana, about one mile north of "Old Baldy."

VIII. *Livingston Peak.*—On the south slope of Livingston Peak, on the ridge leading to "Old Baldy" (the 9,500-foot peak 1 mile southwest of Livingston Peak), Livingston quadrangle, Montana.

IX. *Logan, Montana.*—On the ridges north of the Gallatin River, opposite Logan, in the Three Forks quadrangle, Montana.

X. *Teton River.*—On the divide between Teton River and South Leigh Creek, Grand Teton quadrangle, Wyoming.

XI. *Blacksmith Fork* (including the Cambrian).—Measured across the ridges just north of the canyon of Blacksmith Fork, Cache County, Utah, from Cottonwood Gulch to the crest of Logan Peak, west of Saddle Creek.

XII. *Manitou.*—Measured on the ridges from one to two miles northwest of Manitou, Colorado.

STRATIGRAPHY

THE CORRELATION DIAGRAMS

Use of the diagrams.—Detailed descriptions of the 12 sections above listed cannot be printed here. A consistent application of the principles of correlation outlined on pp. 115, 122, however, has made it possible to formulate a standard list of members. Each of the 12 sections is made up of a part or all of the members in this list (see pp. 123–28), and includes no others. By combining these members in the manner indicated by the accompanying correlation tables (Figs. 2, 3) and diagrams (Figs. 4, 5), every one of the 17 stratigraphic sections used in the compilation of the list can be reconstructed. For instance, the Devonian system in the Crandall Creek section is made up of Member 1, with a thickness of 47 feet, overlain by Member 2, 26 feet thick, which is followed by Member 3, 28 feet thick, and so forth. Even if some of the strata in a given section be erroneously placed in the correlation table, yet the table and the standard list of members will furnish a correct description of that section, with accurate measurements of its constituent parts.

The description of each member is given in considerable detail, but is sufficiently generalized in each case to cover all observed variations in character from place to place. In the few cases where

FIG. 1.—Map showing localities referred to in this paper

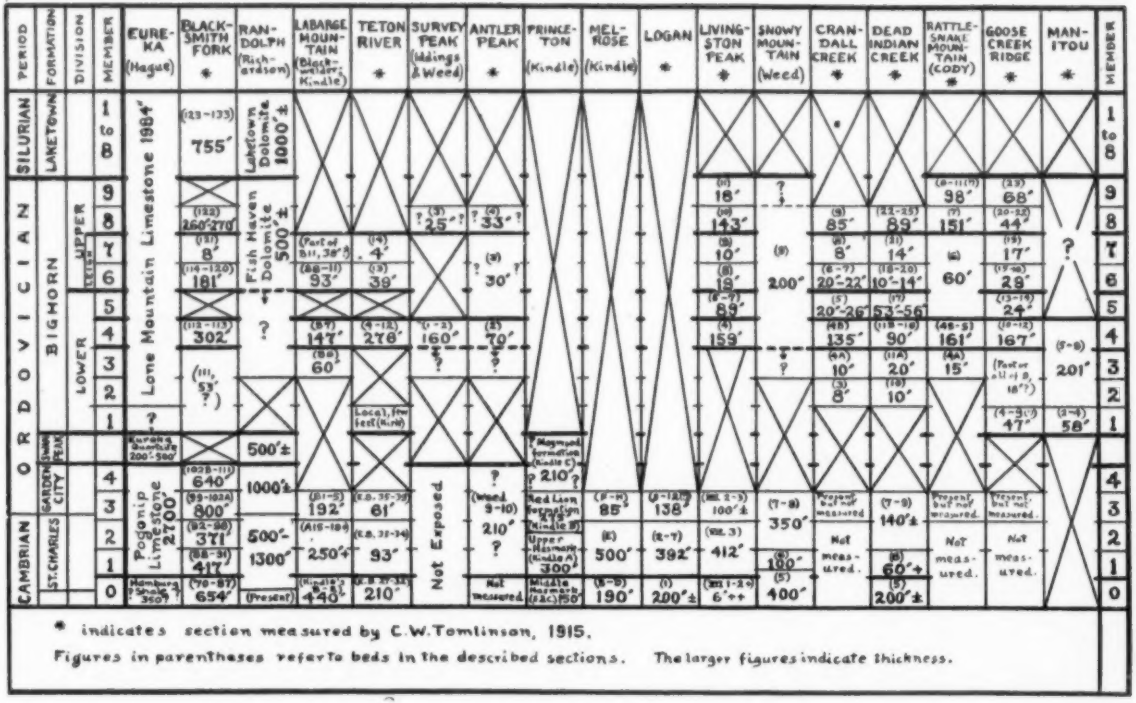

FIG. 2.—Correlation table for the Cambrian, Ordovician, and Silurian systems

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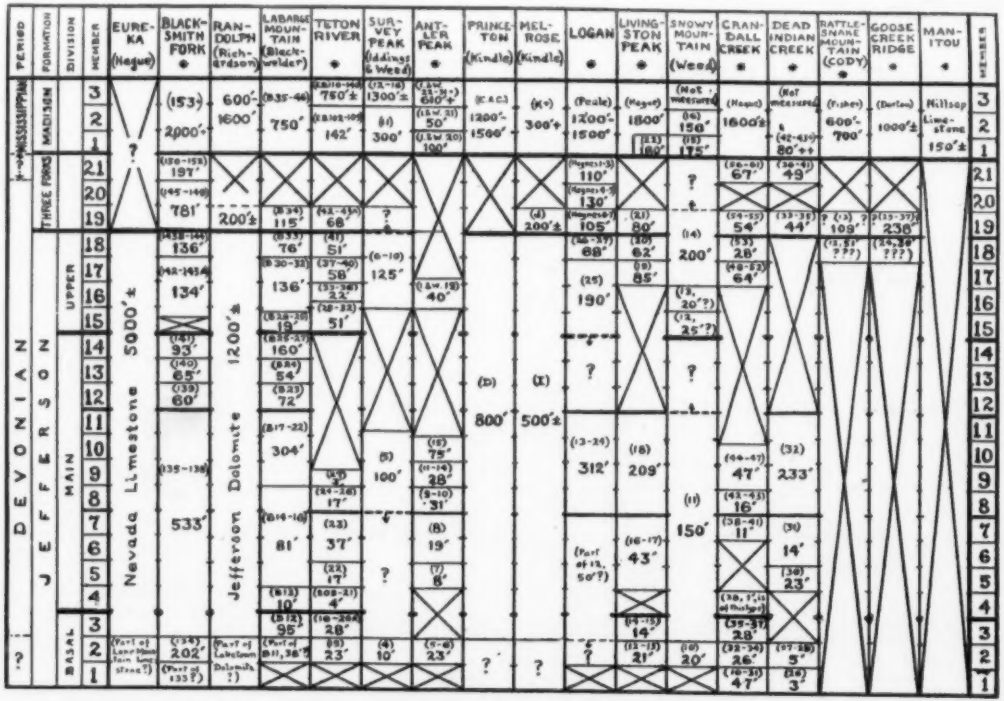

FIG. 3.—Correlation table for the Devonian system

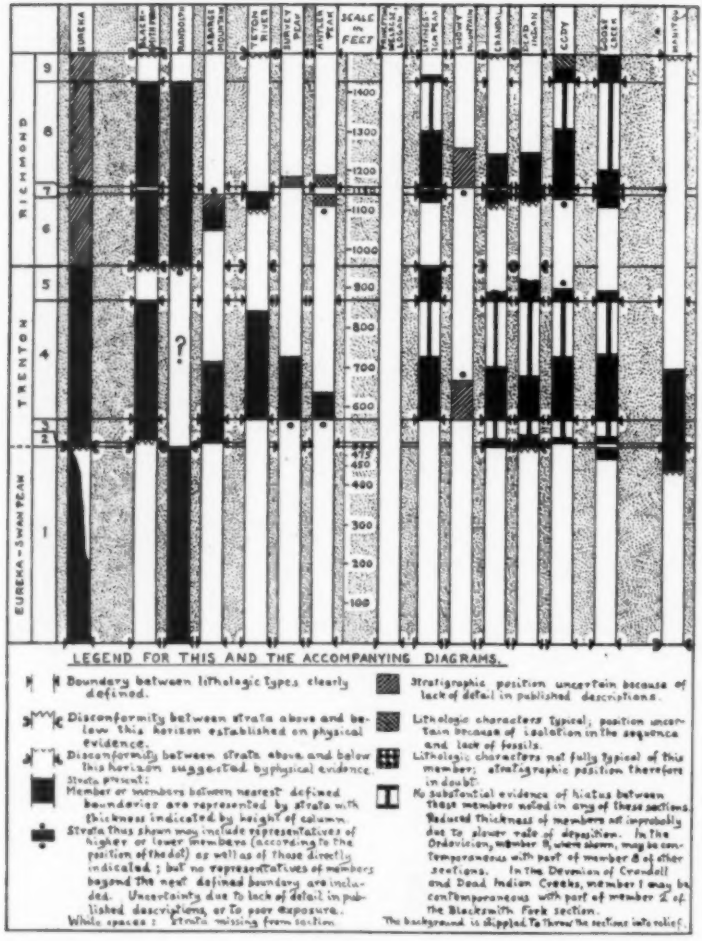
EUREKA
BLACK-SMITH FORK
MARDOCK
VENNICE MOUNTAIN
TETON RIDGE
SURVEY PEAK
SWAN PEAK
SCALE IN FEET
WHITEROCK CANYON
LEPPER CANYON
HOGUP MOUNTAIN
CRANDELL
DEAD INDIAN
CODY
COOKE CANYON
RICHMOND
TRENTON
EUREKA-SWAN PEAK
LEGEND FOR THIS AND THE ACCOMPANYING DIAGRAMS.
Boundary between lithologic types clearly defined.
Disconformity between strata above and below this horizon established on physical evidence.
Disconformity between strata above and below this horizon suggested by physical evidence.
Strata present:
Member or members between nearest defined boundaries are represented by strata with thickness indicated by height of column.
Strata thus shown may include representatives of higher or lower members (according to the position of the dot) as well as of those directly indicated; but no representatives of members beyond the next defined boundary are included. Uncertainty due to lack of detail in published descriptions, or to poor exposure.
White spaces: Strata missing from section.
Stratigraphic position uncertain because of lack of detail in published descriptions.
Lithologic characters typical; position uncertain because of isolation in the sequence and lack of fossils.
Lithologic characters not fully typical of this member; stratigraphic position therefore in doubt.
No substantial evidence of hiatus between these members noted in any of these sections. Reduced thickness of members all improbably due to slower rate of deposition. In the Ordovician, member B, where shown, may be contemporaneous with part of member A of other sections. In the Devonian of Crandell and Dead Indian Creeks, member I may be contemporaneous with part of member L of the Blacksmith Fork section.
The background is stippled to throw the sections into relief.

FIG. 4.—Correlation diagram for the Ordovician system, drawn to scale

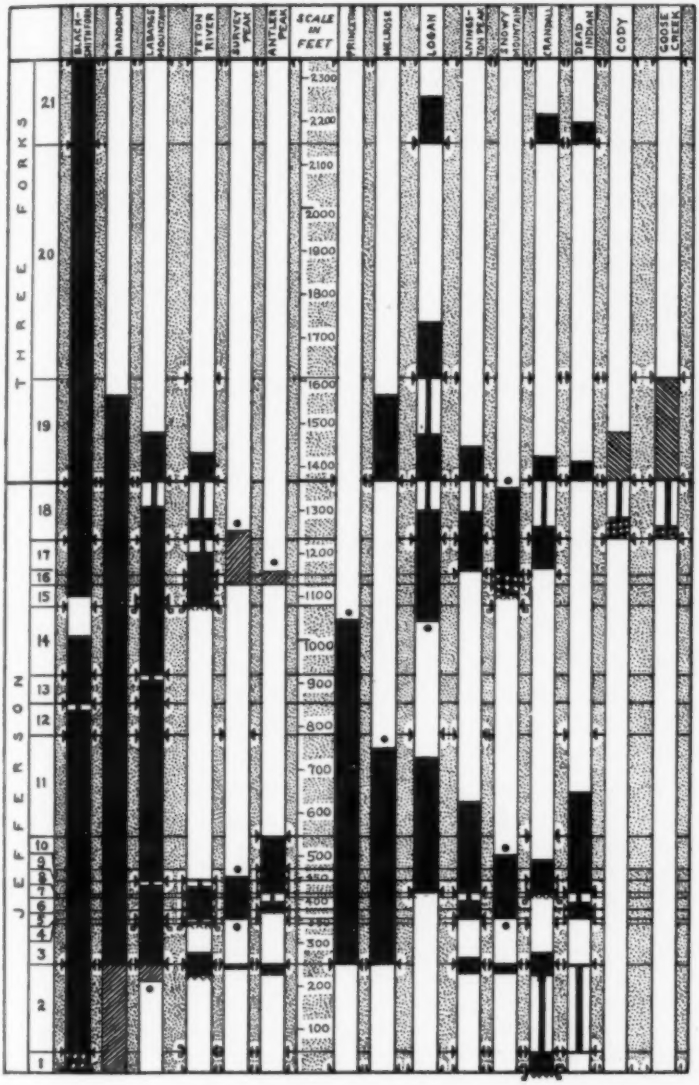

FIG. 5.—Correlation diagram for the Devonian system, drawn to scale

such variations are conspicuous or important they are specifically described for the locality where they were noted.

The standard list of members, together with the detailed correlation tables (Figs. 2, 3), in effect furnishes a compound section for 17 different localities in the central Rocky Mountain region.

Method of correlation.—In making the correlations here set forth the notes and the specimens from each section were carefully compared with the notes and the specimens from every other section, at first singly, then in groups. When a thorough and comprehensive tentative plan of correlation had been completed, all of the specimens from all the sections were laid out on a specially prepared floor, marked off into intersecting columns and rows, so that comparison of all the specimens thought to belong to a given horizon could be made at once, and at the same time all possible alterations in the proposed plan of correlation could be considered with the specimens in view. Happily, the original plan stood the test with very few changes, and those were of minor consequence.

All available paleontological data were carefully studied to determine as accurately as possible the age of the several members.

This correlation is not to be considered as final in all details, and even a few of its larger features are still clouded by uncertainty due to lack of data. The points in doubt are indicated in the diagrams and discussed in the pages following.

Sources of data.—The 7 sections, other than those measured by the writer, which are embodied in the correlation were taken from the following sources:

Eureka District, Nevada.—Arnold Hague, "Geology of the Eureka District, Nevada," *U.S. Geol. Survey, Monographs*, XX (1892).

Randolph quadrangle, Utah.—G. B. Richardson, "The Paleozoic Section in Northern Utah," *Amer. Jour. Sci.*, 4th Ser., XXXVI (1913), 406–18.

Labarge Mountain, Wyoming.—Eliot Blackwelder, unpublished manuscripts, *U.S. Geol. Survey;* E. M. Kindle, "The Fauna and Stratigraphy of the Jefferson Limestone in the Northern Rocky Mountain Region," *Bull. Amer. Pal.*, IV, No. 20 (1908), 12–13.

Survey Peak, Wyoming.—J. P. Iddings and W. H. Weed, "Descriptive Geology of the Northern End of the Teton Range," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. iv, p. 180.

Princeton, Montana.—E. M. Kindle, *op. cit.*, p. 10.

Melrose, Montana.—E. M. Kindle, *op. cit.*, p. 9.

Snowy Mountain, Wyoming.—W. H. Weed, "Geology of the Southern End of the Snowy Range," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. vi, pp. 206, 213–14.

With the exception of Blackwelder's section at Labarge Mountain none of these was described in detail, and the correlation given for them is of necessity very general and subject to thoroughgoing revision.

Additional data on the thickness of Cambrian and Mississippian members were secured from the following sources:

Teton River, Wyoming.—Eliot Blackwelder, unpublished manuscripts, *U.S. Geol. Survey.*

Antler Peak, Wyoming.—J. P. Iddings and W. H. Weed, "Descriptive Geology of the Gallatin Mountains," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. i, p. 22.

Logan, Montana.—A. C. Peale, "Description of the Three Forks (Montana) Sheet," *Geol. Atlas U.S.*, Folio 24 (1896).

Livingston Peak, Montana.—Arnold Hague, "Description of the Livingston (Montana) Sheet," *Geol. Atlas U.S.*, Folio 1 (1894).

Crandall Creek, Wyoming.—Arnold Hague, "Description of the Absaroka Quadrangle," *Geol. Atlas U.S.*, Folio 52 (1899).

Rattlesnake Mountain, Wyoming.—C. A. Fisher, "Geology and Water Resources of the Bighorn Basin, Wyoming," *U.S. Geol. Survey, Prof. Paper No. 53* (1906), p. 14.

Goose Creek Ridge, Wyoming.—N. H. Darton, "Description of the Bald Mountain and Dayton Quadrangles," *Geol. Atlas U.S.*, Folio 141 (1906).

Princeton, Montana.—W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *U.S. Geol. Survey, Prof. Paper No. 78* (1913).

Data concerning the Three Forks formation near Logan, Montana, were taken from:

W. P. Haynes, "The Fauna of the Upper Devonian in Montana, Part 2, The Stratigraphy and the Brachiopoda," *Annals of the Carnegie Museum*, X (1916), 16–17.

STANDARD LIST OF MEMBERS

CONSTITUTING THE MIDDLE PALEOZOIC SECTION IN WESTERN WYOMING, SOUTHWESTERN MONTANA, AND NORTHEASTERN UTAH

(M.T. = Maximum thickness known in this region)

MISSISSIPPIAN

3. Main body of the Madison limestone. Interbedded massive and flaggy limestones, blue-gray, gray, brown, or black, crystalline to dense, with some layers abundantly fossiliferous. Chert of local occurrence only. M.T.,

2,000 feet, more or less, in Utah. 1,500 feet in the Livingston quadrangle, Montana.

2. Coarsely crystalline, very fossiliferous limestone, free from chert. M.T., 150 feet, Snowy Mountain section, Yellowstone Park.

1. Very hard, cherty, black or gray limestone. Fossils few or fragmentary. M.T., 175 feet, Snowy Mountain. (Members 1 and 2 of the Mississippian are differentiated from Member 3 only in Yellowstone Park and vicinity.)

DEVONIAN

(Member 21 may prove to be of Mississippian age; Members 1 and 2 may be Silurian.)

Three Forks Formation

(M.T., 978 feet, Blacksmith Fork)

21 (=Haynes's 1, 2, and 3). Thin-bedded or papery black shales, overlain by yellow or reddish sandstones, sandy shales, or arenaceous limestones. M.T., 197 feet, Blacksmith Fork.

. . . . . Break in Sedimentation . . . . . .

20B. Blue-gray platy or nodular limestone. M.T., 361 feet, Blacksmith Fork (Beds 146B–149).

20. (=Haynes's 4 and 5). Fissile green shale, capped by nodular gray limestone, both very fossiliferous; the horizon of the *Clymenia* fauna in Montana. 130 feet, Logan, Montana. M.T., of Members 19 and 20 together, 420 feet, Blacksmith Fork (Beds 146–146A).

19. (=Haynes's 6 and 7). Orange-yellow to reddish platy limestones and calcareous shales (drab to cream or yellow on fresh surfaces). 109 feet, Logan (238 feet, Goose Creek Ridge).

Upper Division of the Jefferson Dolomite

(M.T., 270 feet, Blacksmith Fork)

18. Brecciated ($\frac{1}{4}$-inch to $\frac{3}{4}$-inch fragments) drab to gray-brown, massive dolomite, in most places forming cliffs. M.T., 136 feet, Blacksmith Fork.

17. Drab, yellow, and buff to dark-brown, thin-bedded limestones or dolomites, locally in part shaly. M.T., 85 feet, Livingston Peak.

16. Moderately massive dolomite, gray to brown, with rough surface. Sparingly fossiliferous in Yellowstone Park. M.T., 40 feet, Antler Peak (Iddings and Weed).

15. White or variegated sandstone, locally represented by light-gray dolomite full of coarse quartz grains, or by limestone conglomerate(?) (Snowy Mountain). In the Teton River section, interbedded with dark-brown,

pitted dolomite, probably representing part of Member 16. 19 feet, Labarge Mountain; 51 feet total, Teton River.

. . . . . Break in Sedimentation . . . . . .

Main Division of the Jefferson Dolomite

(M.T., 681 feet, Labarge Mountain)

14. Imperfectly exposed. Ledges of fine-grained, brown dolomite. Float of thin-bedded, drab and buff dolomite also. M.T., 160 feet, Labarge Mountain.

13. Cliff-making, steel-gray or gray-brown, fine-grained, calcitic, pitted dolomite. M.T., 65 feet, Blacksmith Fork.

12. Very poorly exposed. Float of thin-bedded, light-gray and buff dolomite, very calcitic, grayish-brown dolomite, and calcareous shale. M.T., 72 feet, Labarge Mountain.

8–11. Main body of the Jefferson dolomite in Wyoming and Montana. Blackish to light-brown and brownish-gray, thick-bedded dolomite, weathering to brown-gray or gray. Very fetid odor on fresh fracture. Characteristically with a rough weathered surface. Locally calcitic, or with some layers mottled and streaked with buff. Locally quite fossiliferous at certain horizons. 312 feet, Logan; probably somewhat more at Labarge Mountain and at Blacksmith Fork.

10. (Differentiated at Antler Peak only.) Brown and drab to whitish dolomite with yellow-brown bands. M.T., 75 feet, Antler Peak.

9. Dark-brown, saccharoidal, fetid dolomite, with rough weathered surface. M.T., 28 feet, Antler Peak.

8B. White, drab, or pearl-gray dolomite, conspicuous because of its light color. M.T., Labarge Mountain (Bed 16), 3 feet; Teton River (Bed 26), 1 foot 6 inches; Antler Peak (Bed 10), 3 feet; Crandall Creek (Bed 43), 2 feet 6 inches.

8A. Light-brown to blackish-brown, fine-grained dolomite. M.T., 28 feet, Antler Peak.

6–7. Dense to finely crystalline, white, cream, or pale-gray dolomite, platy to blocky. M.T., 37 feet, Teton River. In the Crandall Creek section sedimentation appears to have recommenced with Member 7 after an interval of nondeposition.

5. Fine-grained or saccharoidal, dark-brown, fetid dolomite, with irregular, pitted, weathered surfaces. M.T., 23 feet, Dead Indian Creek.

4. White friable sandstone at Labarge Mountain, elsewhere represented, like Member 15, by a bed of quartz grains more or less closely packed together in a matrix of white or yellowish dolomite. M.T., 10 feet, Labarge Mountain.

. . . . . Break in Sedimentation (?) . . . . . .

Basal Division of the Jefferson Dolomite

(M.T. for Wyoming, 101 feet, Crandall Creek)

3. Fetid, dark-brown, saccharoidal dolomite, mostly thin-bedded. M.T., 95 feet, Labarge Mountain.
2. White, light-drab, or very pale lavender, dense or finely crystalline dolomite, breaking up into small, sharply angular talus. Locally carries ostracods. M.T., 202 feet, Blacksmith Fork. (Probably included with the Silurian by Kindle and Richardson in Utah because of its light color. Possibly of Silurian age.) Lies directly on the Ordovician in many sections, locally with marked disconformity.
1. (Typically developed in the Crandall Creek section only.) Thin-bedded, greatly variegated dolomite, with thin bands of red shale and black chert. Dolomites saccharoidal to very dense and closely laminated. Thin limestone conglomerate at the base. Lies directly upon the Ordovician at Crandall Creek. M.T., 47 feet, Crandall Creek.

. . . . . Break in Sedimentation . . . . . .

(In Wyoming and Montana; not in Utah?)

SILURIAN

(Not known in Wyoming, Montana, or Colorado; typically developed at Blacksmith Fork, Utah, where it includes the following members:)

8. Massive, brown-gray dolomite, medium finely crystalline, with rough weathered surface. 190 feet.
7. Thin-bedded, slabby limestone. 5 feet.
6. Massive, pearl-gray or whitish limestone, medium finely crystalline, with hackly talus; lower 45 feet contains abundant nodules of snow-white chert like Member 5. 140 feet.
5. Massive white chert, with many quartz geodes. 10 feet.
4. Extremely massive, cream-colored, coarsely crystalline dolomite. Upper 20 feet contains much chert like Member 5. Basal 5 feet full of internal casts of a Pentamerid shell. 145 feet.
3. Massive, cream-colored or brownish dolomite, medium fine-grained, weathering to smooth surfaces. 15 feet.
2. Like Member 8. 138 feet.
1. Like Member 4. Basal 20 feet crowded with casts of Pentamerids and corals. 112 feet.

. . . . . Marked Disconformity . . . . . .

MIDDLE AND UPPER ORDOVICIAN

Richmond (Upper Bighorn, Upper Fish Haven)

9. White to light-gray or buffish, dense to coarsely crystalline dolomite, mostly thin-bedded. Less resistant than Member 8. Cherty and very fossiliferous at Goose Creek Ridge. M.T., 68 feet, Goose Creek Ridge.

8. Cliff-making, massive dolomite, locally with algal structure. Light-buff to brownish (dark-brown at Blacksmith Fork). In the Absaroka Range, partly brecciated, mottled, brownish fragments in buff matrix. Sparingly fossiliferous at Goose Creek Ridge. M.T., 270 feet, Blacksmith Fork.
7. White to dark-drab or brown-gray, dense dolomite. Weak, breaking to small angular fragments. Locally carries ostracods. M.T., 17 feet, Goose Creek Ridge.
6. Basal dolomitic breccia or conglomerate (not seen in Goose Creek Ridge section), interleaving with, and giving place upward to, a massive, brown-gray dolomite containing much calcite in seams and geodes, or to white or drab, finely crystalline dolomite somewhat similar to Member 5. The white dolomite carries corals at Goose Creek Ridge. M.T., 181 feet, Blacksmith Fork, where the two types of dolomite above described occur interbedded.

Trenton (Lower Bighorn)

5. Typically white, almost chalky, fine-grained dolomite, breaking into small angular fragments with relatively smooth weathered surfaces. At Livingston Peak interbedded with more coarsely crystalline, brownish dolomite. Locally carries ostracods. 56 feet, Dead Indian Creek (typical throughout). M.T., 89 feet, Livingston Peak.
4. Cliff-making, massive (rarely slabby), white to light-gray or light-buff dolomite, medium to very coarsely crystalline, in many places in part with brecciated structure. Sparingly fossiliferous in many localities. 147 feet, Labarge Mountain. M.T., 153 feet, Blacksmith Fork, where it is underlain by 149 feet of massive, dark-brown dolomite, medium finely crystalline, with many seams of calcite (both members included under Member 4 in the diagrams).
3. Like Member 4, but thin-bedded or closely jointed, weak. M.T., 60 feet, Labarge Mountain.
2. (Recognized in the Crandall Creek and Dead Indian Creek sections only.) Cream to buff, finely crystalline dolomite in 2-foot beds. Fossiliferous. M.T., 10 feet, Dead Indian Creek.
1. In Wyoming, developed as a white to buff or rose sandstone, mostly soft and friable; fossiliferous, locally with fish remains. 29 feet (plus ?), Goose Creek Ridge. Correlated with the Harding sandstone of Colorado. At Manitou, very arkosic, and in part deeply stained (red and green); 47 feet thick. Possibly contemporaneous with part of the Swan Peak quartzite. Possibly of Black River rather than Trenton age.

. . . . . Marked Disconformity . . . . . .

Swan Peak Quartzite

Five hundred feet thick, in the Randolph quadrangle, northern Utah. Geneva sandstone or quartzite, north end of the Wasatch Mountains, Utah. Eureka quartzite, 200 to 500 feet thick, east-central Nevada.

UPPER CAMBRIAN AND EARLY ORDOVICIAN

4. (Known at Blacksmith Fork only.) 640 feet. Includes the following types, in descending order:

   Thin-bedded, light-gray, finely crystalline dolomite; in the upper part interbedded with olive shales and very fossiliferous. 206 feet. (Beekmantown.)

   Fossiliferous, dark blue-gray or blue-black, very finely crystalline dolomite with much black chert throughout, and a 30-foot bed of black chert at the base. 156 feet. (Beekmantown.)

   Brownish-gray to bluish-gray, finely to coarsely crystalline dolomite in 1-foot to 5-foot beds. 278 feet.

3. Mostly thin-bedded to shaly, bluish-gray to brownish-gray, finely crystalline dolomite and dolomitic shale, with many layers of *flat-pebble limestone conglomerate*. In part fossiliferous. M.T., 800 feet, Blacksmith Fork (lower 190 feet, Upper Cambrian, placed in the St. Charles formation by Walcott; remainder Ordovician). This member is represented throughout northern and western Wyoming and southwestern Montana.

2. (Not differentiated except at Blacksmith Fork.) Finely to coarsely crystalline, gray dolomite, mostly thin-bedded, weak; in part oolitic. 349 feet, Blacksmith Fork.

1. Very massive, cliff-making, coarsely crystalline white dolomite, interbedded near the top and bottom with minor beds of thinner-bedded gray dolomite. M.T., 412 feet, Livingston Peak.

0. Mostly thin-bedded, white to light- and dark-gray, finely to coarsely crystalline dolomite, locally with much sandstone in lower part, and with interbedded flat-pebble limestone conglomerate. In part fossiliferous. Lower (barren) half called Middle Cambrian by Walcott at Blacksmith Fork (upper part of the Nounan formation). M.T., 654 feet, Blacksmith Fork.

PALEONTOLOGICAL COLLECTIONS: ASSEMBLED LISTS

DEVONIAN

Members 5–11:

Actinostroma sp. Antler peak, Livingston Peak.
Alveolites goldfussi Billings. Livingston Peak.
Anplexus cf. *hamiltoniae* Hall. Antler Peak.
Blothrophyllum(?) cf. *cinctutum* Davis. Antler Peak.
Zaphrentis(?) sp. Livingston Peak.
Atrypa missouriensis Miller. Livingston Peak.
Bryozoa. Antler Peak, Livingston Peak (2 sp.).

Member 3:

Atrypa missouriensis Miller (fragmentary). Teton River.

Member 2:

Unidentifiable brachiopod and gastropod fragments. Teton River.
Leperditia sp. Livingston Peak, Teton River (2 sp.).

SILURIAN (BLACKSMITH FORK ONLY)

Member 8, 10 feet below top:
Syringopora cf. *verticillata* Goldfuss.

Member 4, base:
Favosites sp.
Zaphrentis(?) sp.
Conchidium knighti Sowerby.
Pentamerus cf. *oblongus* Sowerby.

Member 2:
Syringopora sp.

Member 1:
Favosites sp.
Conchidium knighti Sowerby.
Pentamerus cf. *oblongus* Sowerby.

UPPER ORDOVICIAN (RICHMOND)

Member 9. (Goose Creek Ridge only.)
Calapoecia(?) cf. *anticostiensis* Billings.
C. cribriformis (Nicholson).
Favosites (n.sp.?).
Halysites gracilis (Hall).
Streptelasma sp.
Crinoid fragments.
Rhynchotrema sp.
Zygospira modesta(?) Hall
Orthoceras(?) sp.
Bryozoa.

Member 8:
Calapoecia sp. Blacksmith Fork.
Streptelasma sp. Goose Creek Ridge, Blacksmith Fork.
Dalmanella cf. *testudinaria* (Hall) and *hamburgensis* (Walcott). Goose Creek Ridge.
Orthoceras(?) sp. Goose Creek Ridge.

Member 7:
Crinoid fragments. Dead Indian Creek.
Dalmenella(?) sp. Crandall Creek, Teton River(?).
Leperditia sp. Goose Creek Ridge, Crandall Creek, Teton River.

Member 6:
Calapoecia(?) cf. *anticostiensis* Billings. Goose Creek Ridge.
Columnaria sp. Dead Indian Creek.
Halysites gracilis (Hall). Goose Creek Ridge.
Cf. *Protarea richmondensis* Foerste. Goose Creek Ridge.
Streptelasma sp. Goose Creek Ridge.
Pachydictya fenestelliformis(?) Nicholson. Goose Creek Ridge.
Rhinidictya cf. *mutabilis* (Ulrich). Goose Creek Ridge.

MIDDLE ORDOVICIAN

Member 4:

Spheroidal algae. Teton River.

Receptaculites oweni Hall. Livingston Peak.

Lichenaria cf. *typa* Winchell and Schuchert. Rattlesnake Mountain.

Columnaria alveolata Goldfuss. Rattlesnake Mountain, Dead Indian Creek, Crandall Creek.

Halysites gracilis (Hall). Blacksmith Fork.

Streptelasma corniculum Hall. Goose Creek Ridge, Dead Indian Creek (sp.?), Crandall Creek.

A new cyathophyllid coral. Crandall Creek.

Member 2:

Receptaculites oweni Hall. Crandall Creek.

Halysites gracilis (Hall). Dead Indian Creek, Crandall Creek.

Streptelasma corniculum Hall. Crandall Creek.

Zygospira sp. Crandall Creek.

Clinoceras(?) sp. Crandall Creek.

Member 1, within 5 feet of top (Goose Creek only):

Lophospira sp.

Raphistoma(?) sp.

Cyrtoceras(?) sp.

Orthoceras sp.

Receptaculites oweni Hall.

EARLY ORDOVICIAN (BEEKMANTOWN) (BLACKSMITH FORK ONLY)

Member 4, near top:

A small *Streptelasma*-like coral.

A small cylindrical bryozoan.

Several species of orthid and strophomenoid brachiopods, including a form probably identical with that called by Walcott[1] "*Orthis testudinaria*," from the Upper Pogonip; a form very similar to, and perhaps identical with, the one called by White[2] "*Strophomena fontinalis*"; and a form which is probably identical with that called by Walcott[3] "*Orthis pervela*."

Two species of low-spired gastropods.

Orthoceras sp. (small, annulated form).

[1] C. D. Walcott, "Paleontology of the Eureka District, Nevada," *U.S. Geol. Survey, Monographs*, VIII (1884).

[2] C. A. White, "Invertebrate Paleontology: Report upon Geographical and Geological Surveys West of the One Hundredth Meridian," IV, Part 1 (1875), Engineer Department, United States Army.

[3] *Op. cit.*

Cf. *Bathyurus*? (*Hystricurus*?) *tuberculatus* Walcott.
Ceraurus(?) sp.
An *Isotelus*-like pygidium.

Member 4, 390 feet above base:
Lingula, 2 sp.
Two species of strophomenoid brachiopods; the same as the first two of the three forms mentioned in the fauna collected near the top of Member 4.
Orthoceras sp. (small, annulated form).
Asaphus(?) sp.
Ceraurus(?) sp.

UPPER CAMBRIAN

Member 3.
Billingsella coloradoensis(?) (Shumard). Antler Peak.
Eoorthis cf. *remnicha* Winchell. Teton River.
Obolella(?) sp. Teton River.
Agnostus sp. Teton River.
Ptychoparia(?) sp. Antler Peak, Teton River(?).
Trilobite fragments. Blacksmith Fork.

Member 2:
Unidentifiable organic (algal?) structures. Blacksmith Fork.

Member 1:
Spheroidal algae, ¼ inch to 2 inches in diameter. Blacksmith Fork.

Member 0, top (Blacksmith Fork only):
Billingsella coloradoensis (Shumard).
Lingulella manticula (White).
Agnostus.
Ptychoparia.

DISCONFORMITIES

In the following statement is listed the evidence pointing toward discontinuity of sedimentation at the several horizons indicated.

8. Between Members 20 and 21 of the Devonian system (between Devonian and Mississippian?):

a) Member 20B, a limestone, 361 feet thick at Blacksmith Fork, has no lithologically similar representative in any of the other sections, unless it be a 10-foot limestone at Logan, Montana.

b) Member 21 rests on Member 19 at Crandall Creek and at Dead Indian Creek.

c) At Labarge Mountain, Teton River, and Livingston Peak, according to the writer's interpretation, the Madison limestone rests directly on Member 19.

d) Where Members 20B and 21 are absent, the thickness of Member 19 is variable, though not extraordinarily so.

e) Member 21 consists of clastic sediment, chiefly sandstone and black or deeply stained shale.

f) Member 21 contains "a fauna which is different in most of its forms from that of the lower members, and is more like that of the Madison limestone"[1] which overlies it.

7. Between Members 18 and 19 of the Devonian system (between the Jefferson limestone and the Three Forks formation):

a, Sharp lithologic change at this horizon.

b, Member 18 is moderately variable in thickness.

c, In the Teton River section the base of Member 19 contains nodules of limonite. In the Crandall Creek section the same horizon is very deeply iron-stained and carries small geodes of amorphous hematite.

It will be noted that this evidence is entirely circumstantial.

6. Between Members 14 and 15 of the Devonian system (between the main and upper divisions of the Jefferson dolomite):

a) There is a 16-foot sandstone at this horizon in the Labarge Mountain section, and much sandstone in Member 15 in the Teton River section.

b) Members 11–14, with a maximum aggregate thickness of 550 feet, are absent in the Teton River, Antler Peak, and Crandall Creek sections.

c) Members 12–14 are not known north of Labarge Mountain.

d) The Nevada limestone of eastern Nevada includes a lower and an upper fossiliferous zone, separated by from 2,000 to 4,000 feet of barren beds. The Jefferson fauna includes elements of both of the fossiliferous zones of the Nevada, suggesting that the great thickness of the Nevada is due to the presence of medial barren members which are not found in the Jefferson.[2]

e) In the Snowy Mountain section in Yellowstone Park, Weed[3] describes a 25-foot belt of limestone conglomerate at what may be this horizon.

5. Between Members 3 and 4 of the Devonian system (between the basal and main divisions of the Jefferson dolomite):

a) There is a 10-foot bed of sandstone (Member 4) at this horizon in the Labarge Mountain section, and a thinner bed of extremely sandy dolomite in

[1] W. P. Haynes, "The Fauna of the Upper Devonian of Montana, Part 2, The Stratigraphy and the Brachiopoda," *Annals of the Carnegie Museum*, X (1916), 27. It is to be noted that Haynes reached the conclusion that, nevertheless, "there is no sharp break in the record here" (*ibid.*, p. 20).

[2] See discussion of "The Jefferson Dolomite."

[3] W. H. Weed, "Geology of the Southern End of the Snowy Range," *U.S. Geol. Survey, Monographs*, XXXII, Part 2 (1899), chap. vi, p. 206.

the Teton River and Crandall Creek sections marks the base of the main division of the Jefferson.

b) Member 3 was not recognized in the Antler Peak or Dead Indian Creek sections, and in no known section north of Labarge Mountain does it have more than a small fraction of its thickness in that locality.

c) No part of the basal division of the Jefferson was recognized in the Logan section.

4. At the base of the Devonian system:

a) The Silurian system, 750 or more feet thick in northern Utah, is not known in Wyoming or in Montana.

b) The Upper Bighorn dolomite, which underlies the Devonian in western Wyoming and in part of southern Montana, varies greatly in thickness in that region.

c) Members 8 and 9 of the Ordovician system, which elsewhere attain a net thickness of 270 feet, are not found in the Teton River section.

d) In Montana, west of the Gallatin Range, the Devonian system rests on Cambrian strata.

To summarize points (*a*) to (*d*), the Devonian system in different parts of the central Rocky Mountain region rests upon the Silurian, the Ordovician, and the Cambrian, respectively.

e) In the Teton River section an erosion surface marks the base of the Darby formation.[1]

f) In the Crandall Creek section there is at this horizon a thin conglomerate of small rounded pebbles of dolomite in a matrix of laminated, iron-stained shale, overlain by thin lenses of very deeply iron-stained shale. The basal bed varies notably in thickness within a few yards along the strike, showing that it was deposited upon an irregular surface.

It is obvious that there is a hiatus at the base of the Devonian system wherever the Silurian is missing.

3. At the base of the Silurian system:

a) In the Blacksmith Fork section there is an indubitable erosional disconformity at this horizon.

b) The brachiopod fauna above this disconformity is wholly different from any found below it.

2. Between Members 5 and 6 of the Ordovician system (between the Trenton series and the Richmond series, Lower and Upper Bighorn, Lower and Upper Fish Haven, Lower Bighorn and Leigh):

a) In the Crandall Creek, Dead Indian Creek, and Teton River sections there is a well-marked erosional unconformity at this horizon. (Also at the

[1] Eliot Blackwelder, personal note.

base of the Fish Haven dolomite in the Randolph quadrangle, Utah; but this may perhaps be at the base of the Trenton.)

b) In the Crandall Creek, Dead Indian Creek, and Teton River sections there is at the base of the Upper Bighorn (or Leigh) a breccia or conglomerate of dolomite pebbles in dolomitic or shaly matrix, up to several feet thick; and similar conglomerate occurs at the base of the Upper Fish Haven in the Blacksmith Fork section.

c) Thin lenticular bands of deeply stained shale appear in and above the conglomerate in the Dead Indian Creek section, and the matrix of the conglomerate is deeply iron-stained both there and in the Teton River section.

d) Member 5 is not known south or southwest of Cody, Wyoming.

e) A hiatus between Trenton and Richmond was inferred by Darton[1] in the Bighorn Range from paleontological evidence.

1. At the base of the Middle Ordovician series (Lower Bighorn, Lower Fish Haven):

a) Throughout Wyoming, Montana, and South Dakota, wherever the Bighorn formation (or a formation correlated with it) exists it rests upon strata which are classed as Cambrian, and which certainly in no case are younger than Beekmantown.

b) The basal member of the Bighorn at several localities in Wyoming is a sandstone, of variable thickness, suggesting deposition on an uneven surface.[2]

c) In the Dead Indian Creek section the base of the Bighorn is a slightly irregular surface.

d) In the Randolph quadrangle the Fish Haven dolomite (all of Richmond age[?]) rests disconformably on the Swan Peak quartzite.

e) The Swan Peak quartzite is entirely missing from the Blacksmith Fork section, although it is several hundred feet thick a few miles northeast and a few miles southwest of that locality.

f) In eastern Nevada the contact between the Lone Mountain limestone and the Eureka quartzite is clearly an erosion surface.

[1] N. H. Darton, "Description of the Bald Mountain and Dayton Quadrangles," *Geol. Atlas U.S.* (Folio 141, 1906), p. 4.

[2] Cf. N. H. Darton, "A Résumé of the Ordovician Geology of the Northwest," *Bull. Geol. Soc. Amer.*, XVII (1905), 547.

[*To be continued*]

SOME FACTORS AFFECTING THE DEVELOPMENT OF MUD-CRACKS[1]

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INTRODUCTION

Casual examination of the apparently erratic lines known variously as mud-cracks, sun-cracks, and shrinkage-cracks affords little promise of results of interest from their systematic study. The great geologic interest which these products of desiccation possess in connection with the history of formations in which they occur should nevertheless encourage the geologist to ascertain what effect variation in the conditions under which they are formed will have on the resulting kind or type of mud-crack. With the object of ascertaining the nature and extent of the modification of the type of mud-crack which may result from varying the conditions of its formation, I have carried out the laboratory experiments described below. These have been planned with a view to discovering (*a*) the relative effects of rapid and slow desiccation on the same mixture, (*b*) what influence, if any, composition of the mud has upon the mud-cracks, (*c*) the possibility of producing parallel mud-cracks, and (*d*) the differences which distinguish saline from fresh-water mud-cracks.

EXPERIMENTS

Two kinds of clay have been used. In experiments 1 and 3 a mud was used which came from the bottom of Lake Ontario, at a depth of 630 feet, and represented very fine-textured material. The other experiments were made with blue marine clay of Pleistocene age from the Ottawa valley near Ottawa. This is also a very fine-textured and tenacious clay.

Experiment 1.—Lake clay which was thoroughly mixed with about 5 times its volume of fresh water was poured into two

[1] Published with the permission of the Director of the Geological Survey of Canada.

porcelain vessels of the same shape and size, each being completely filled. One of these was set in direct sunlight when the daily noon temperature exceeded 100°, and the other was kept in the shade until the water had evaporated and mud-cracks had developed. The specimen exposed to sunlight developed mud-cracks on the third day. The other vessel showed the first mud-cracks on the eighth day. When completely dried, the mud in the two vessels showed a very marked difference in the size and number of polygons outlined by the mud-cracks developed. The sun-dried mud had cracked into 6 irregular-sided polygons, while the same volume of mud, which had been slowly dried in the shade during a period about three times that given the direct sunlight specimen, showed 26 polygons. Rapid drying thus seems to produce comparatively widely spaced mud-cracks, while slow desiccation gives closely spaced mud-cracks. Some interesting incidental observations were made in connection with this experiment on the tendency displayed by the very fine sand grains to segregate themselves from the mass of the mud and to gather along the edges of the joints and the margin of the vessels holding the mixtures. This segregation of the sand grains resulted in a ring of sand around the outer margin of the mud where it came in contact with the sides of the vessel. Along the sides of many of the mud-cracks the upper angle of the polygon was edged by a continuous border of sand. On the lower side of the polygon edges the sand showed no tendency to segregate. This segregation of the sand along the edges of the mud-cracks appeared to be dependent in part upon the extreme fineness of the grains. An attempt to repeat this phase of the experiment by adding sand of average fineness to mud which was desiccated in the sun failed to show any segregation phenomena, presumably because of the larger size of the sand grains used.

Experiment 2.—This experiment was designed to show what effect variation in the composition of the mud used would have on the character of the mud-cracks. Three parallel experiments were carried out for this purpose. The fine-textured blue clay of Pleistocene age from the Ottawa Valley was used. A mixture of this clay with 3 quarts of water was divided into three equal parts. To one of these (3*a*) was added 2 ounces of fine sand. The same

amount of powdered marl was added to the second (*2b*), while the third lot was left a clay and water mixture (*2c*). These three mixtures, representing sandy mud, marly mud, and clay mud, were placed in three shallow pans for desiccation in the sun. The resulting mud-cracks show that the clay mud (*2c*) cracked into much larger polygons (Fig. 1) than either the sandy or marly mud (Fig. 2). The sandy mud (*3a*) developed more than three times as many

FIG. 1.—Normal fresh-water mud-cracks in blue-clay mud. ¼ natural size

polygons (Fig. 3) as the clay mud, while the marly mud showed more than twice as many polygons as the clay mixture. The large number and very angular course of many of the mud-cracks in the sandy mixture are characteristic features which distinguish this mixture from either of the other two.

Experiment 3.—A portion of the same clay mixture used in experiment 1 was placed in a shallow pan 11 inches in diameter. The water was allowed to evaporate slowly without exposure to

the sun. One side of the pan was raised $\frac{1}{10}$ inch higher than the opposite side, so that near the end of evaporation the lower side remained moist after the upper side had become quite dry, the object being to see what effect, if any, this drying out of the mud in a lateral direction would have on the character of the mud-cracks. The result of this experiment is shown in the photograph (Fig. 4), which was made before the lower margin had entirely dried, the moist portion being indicated by the darker part near the base of the picture. Instead of the usual reticulated mud-crack lines, most of the mud split up into a set of ribbon-like strips averaging $\frac{1}{2}$ inch in width and having a length of 3 to 6 inches. The direction of the mud-cracks which gave this ribbon-like effect was transverse to, and evidently controlled by, the zone separating the completely dried from the

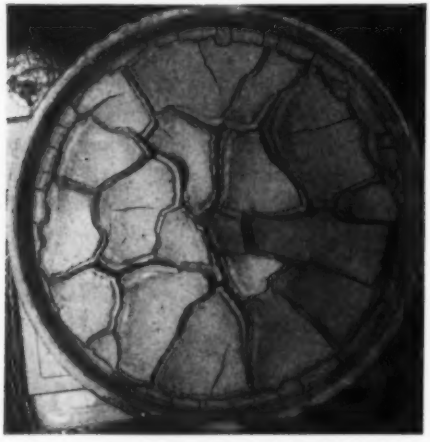

FIG. 2.—Mud-cracks in mud composed of clay and marl. $\frac{1}{4}$ natural size.

FIG. 3.—Mud-cracks in sandy mud. $\frac{1}{4}$ natural size.

partially dried mud (see Fig. 4). The cracks developed with the retreat of this zone away from the area which first dried. In a small patch of this first dried section no mud-cracks formed. This experiment shows that approximately parallel mud-cracks may be developed by differential desiccation, and affords a clue to the cause of certain kinds of joints which appear to be definable as parallel mud-cracks of considerable vertical extent.

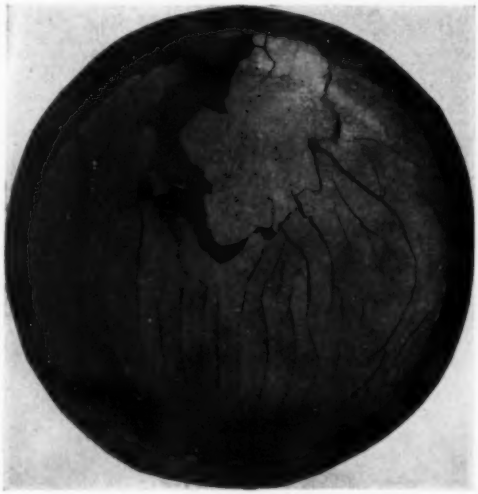

FIG. 4.—Mud-cracks cutting the mud into ribbon-like strips. ¼ natural size

Experiment 4.—A 2-quart mixture of blue clay and water was divided into two equal parts. A tablespoonful of salt was added to one of these, and the other was left fresh. The two mixtures were placed in shallow pans 9½ inches in diameter and put in the sun for evaporation and desiccation. Complete drying or desiccation of the salt-water pan was finished on the eighth day after starting this experiment. The first noted difference between the two pans was the earlier drying out of the saline mixture. All the liquid water had left the salt-water mixture at least a day before the fresh-water mud had ceased to be a semi-liquid mass. The desiccation was finished in a temperature of 110°.

In the fresh-water mixture preliminary mud-cracks developed on a dried-surface layer of the thickness of paper two days before the mixture underneath had lost its semi-liquid character. The earlier drying out of this surface layer of paper-like thinness retarded the drying of the lower layers and led to the excessive curling of the polygons as they were cut out by the developing mud-cracks. A lot of closely curled pieces of sediment resembling shavings repre-

FIG. 5.—Desiccated fresh-water mud. ½ natural size

sented the final stage of the mud-crack development in the fresh-water mixture (see Fig. 5). An interesting feature of this experiment is the difference in color exhibited by the thin uppermost layer, which had been directly exposed to the air and sun, and the sediment below. The topmost film had a lead-gray color, while the sediment below it showed a creamy-white color in no way resembling the original blue clay. The general character of the mud-cracks shown by this pan corresponds closely to those most commonly met with in nature except in the extreme curling of the polygons.

The behavior of the saline mixture was markedly different from that of the fresh-water one. Except for a crack extending round

the margin of the pan and separating the mud adhering to the side from that on the bottom no regular mud-cracks developed until a very late stage of the desiccation. Instead of the usual familiar, somewhat erratic, mud-crack lines seen on drying mud, a five-rayed star-shaped figure (see upper right-hand quarter of Fig. 6) cutting to the bottom of the sediment first appeared. A day later two other figures developed, each having three lines of equal length and form-

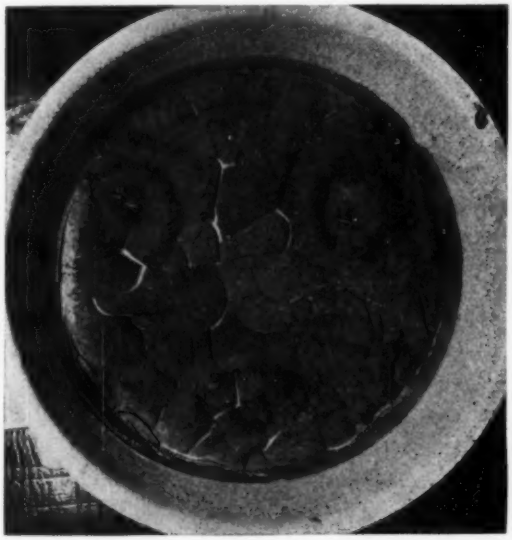

FIG. 6.—Desiccated saline mud. The same quantity and kind of mud was used as in Fig. 5 except that salt was added. Note that margins of polygons are curved downward instead of upward as in the fresh-water mud-cracks shown in Figs. 1, 2, 3, and 5. ½ natural size.

ing at their junction angles of 120°. Simultaneously with the development of the three-line figures the entire surface became marked by small hexagonal polygons with a diameter ranging from ⅛ inch to $\frac{1}{16}$ inch and giving it a honeycomb appearance. These may be seen indistinctly on the left half of Fig. 6. These were not sharply defined nor marked off by mud-crack fissures, but were discernible through a slightly lighter color of the sediment along the bounding lines, and in some cases by a slight deliquescence of

salt along these lines. These small polygons appear to represent the convection cells of Benard,[1] Dauzére,[2] and Sosman,[3] and have no direct relationship to mud-cracks. A few hours after the appearance of the triradiate figures some regular mud-cracks formed in the median portion of the pan, cutting a limited area into rather small polygons. Two of these mud-cracks were extensions of arms of the three-line figures previously mentioned. Two days after the desiccation appeared to have been completed, the remainder of the surface cracked, after being removed from the sun, splitting the entire surface into polygons. A noteworthy feature of these polygons is downwarping of their margins and absence of lateral shrinkage, which is in sharp contrast with the upwarping of the sides and considerable shrinkage of polygons which formed from the fresh-water mud. In fact, the saline mud showed as a whole slight lateral expansion which was taken up by the arching upward of the median portions of the polygons.

Considered from the standpoint of preservation as permanent features in the strata of consolidated rocks, mud-cracks in saline clays would have a rather poor chance of permanent preservation owing to their slight breadth. If preserved, they would be quite inconspicuous as compared with ordinary mud-cracks. The star-shaped figures, however, by reason of their broad and deeply incised arms lend themselves well to preservation under natural conditions of sedimentation and should be regarded, when found on rock surfaces, as evidence of subaërial desiccation. This experiment represents the behavior of highly saline mud such as would be found on the shores of salt lakes or detached arms of the sea rather than that of the muds ordinarily met with about the estuaries of rivers, which have a much lower degree of salinity.

The salinity of ordinary estuarine mud was approximated in another experiment. Sea water was used in still another. In all these supplementary experiments, including a sample of mud having less than the salinity of ordinary tide-flat mud, desiccation produced

[1] H. Benard, *Les Tourbillons cellulaires dans une nappe liquide*, etc., thesis, Paris, 1901; *Rev. gen. Sci.*, XI (1900), 1261–71, 1309–38.

[2] C. Dauzére, *Jour. physique*, VI (1907), 892–99; VII (1908), 930–34; *Assn. franc. av. sci.*; 1908, pp. 289–96.

[3] Robert B. Sosman, "Types of Prismatic Structure in Igneous Rocks," *Jour. Geol.*, XXIV (1916), 219–24.

polygons in which the upper and lower surfaces were perfectly flat, the edges showing no inclination either to warp up or down.

SUMMARY AND DISCUSSION

The experiments described above justify the following deductions: Rapid desiccation produces mud-cracks which are more widely spaced than those produced by slow desiccation. In mud-cracks occurring in rocks of the same or similar composition the relative size of the resulting polygons would therefore serve as a basis for inferring the relative temperatures under which they were formed.

The composition and the resulting tenacity of the mud very materially affects the spacing of the mud-cracks. The presence of marly material or the addition of sand gives polygons which are much smaller than those formed in clay mud (Figs. 1–3). In the case of sandy mud a sufficient excess of sand entirely prevents the formation of mud-cracks. Hence a bed of sand might be exposed to subaërial conditions without furnishing mud-crack evidence of the fact. Temperature and tenacity of the material are two primary factors in controlling the spacing of mud-cracks.

Approximate parallelism of mud-cracks may result from zonal drying of the mud. The parallelism seen in many systems of joint structure may thus be duplicated under special conditions in shrinkage-cracks in mud.

A high degree of salinity delays the formation of mud-cracks and results in polygons in which the margins are inclined downward (Fig. 6). These are in marked contrast to the polygons formed in fresh-water mud, which dish upward, saucer-like (Figs. 1, 2, 3, and 5). The polygons formed in mud with the salinity of ordinary sea water warp neither upward nor downward at the margins, but retain a flat surface. It should be pointed out here that the marked differences observed in the experiments between the behavior of fresh-water, highly saline, and moderately saline muds are not ordinarily so well marked in nature as the accompanying illustrations might lead the reader to expect. The strong tendency, as shown by the pan experiments, of fresh-water mud to warp upward and of very saline mud to warp downward at the margins of the polygons on cracking is modified and often neutralized by

the tenacity of the mud, which on a mud flat may prevent the topmost cracked layers from partially splitting away from the subjacent layers, as they must do if this warping occurs. Clearly the cohesion between the layers of mud is greater than that between the smooth bottom of the pan and the mud in it. Observation of sun-cracked fresh-water mud on the bottom of evanescent ponds will show that the polygons warp upward or remain flat, according to the tenacity of the mud. Where the tenacity of the mud is slight, the saucer-shaped polygons are dominant.

In the case of fossil mud-cracks the geologist can make definite deductions regarding the salinity of the original mud only where there has been distinct upwarping or downwarping of the polygons. Where the surface is flat, as is usually the case, lack of warping is as likely to be due to the tenacity of the mud overcoming the warping influence of fresh water as to the normal influence of the salinity of sea water. Where the polygons show a definite saucer-like upwarp at the margins, however, the inference that they were formed from fresh-water mud would be inevitable. I have described[1] from bed A of the Mount Wissick section in New Brunswick an example of this kind which in the light of these experiments must be referred to continental or fresh-water conditions, although I originally supposed it to have been formed on a tidal flat.

Fossil examples of the inverted-saucer type of polygon due to the drying of very saline muds are apparently not very common. Some peculiar structures in Silurian dolomite described by Gilbert[2] and illustrated[3] by Kindle probably represent a phase of this phenomenon. These curved plates in the Lockport dolomite near Niagara Falls, which are probably the result of the desiccation of highly saline sediments, were supposed by Hall to be of concretionary origin. They immediately precede in the section a rock series in which beds of gypsum and rock salt afford conclusive evidence of the highly saline character of the sediments deposited a little later.

[1] *Geol. Surv., Can. Mus. Bull. 2*, 1914, p. 37.

[2] "Undulations of Certain Layers of the Lockport Limestone" (Abstract), *Science*, N.S., XXI (1905), 224.

[3] *U.S. Geol. Surv. Folio No. 190*, 1914, p. 59, Pl. 24.

DOWNWARPING ALONG JOINT PLANES AT THE CLOSE OF THE NIAGARAN AND ACADIAN[1]

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The upper part of the Lockport dolomite exhibits a number of interesting structural features. These are not confined to the Lockport, but many of them have an important bearing on the physical conditions during and immediately succeeding the formation of the Lockport and as such deserve attention. Among the most striking of these are: (1) the huge vase-like residual masses of the Lockport on Flowerpot Island[2] in the Bruce Peninsula of Ontario; (2) the widespread doming of the strata which Kindle has described[3] as probably analogous in origin to the mud lumps at the mouth of the Mississippi; (3) the arching of the strata forming the uppermost or Eramosa beds of the Lockport dolomite in Ontario, where it is ascribed in at least one instance[4] to the presence of an underlying coral reef; (4) the burial of Devonian rock and fossils in joints 18 feet below the present glaciated surface of the Niagara limestone in Illinois;[5] (5) the anticlinal arches which characterize the Lockport in the Niagara region, and which Kindle and Taylor[6] ascribe to local stresses of comparatively recent date; (6) the ripple-mark and other sedimentation phenomena which have been described so frequently;[7] (7) the immediate superposition above the Lockport of the Salina with its salt and gypsum;[8]

[1] Published by permission of the Deputy Minister of Mines.

[2] Stauffer, *Geol. Surv. of Canada, Guide Book No. 5*, 1913, p. 75.

[3] *Amer. Jour. Sci.*, 4th Ser., XV (1903), 459–68.

[4] Williams, *Geol. Surv. of Canada, Museum Bull. No. 20*, 1915, pp. 1–2. It should be noted, however, that the horizon of the Eramosa beds is below the top of the Lockport as used, for example, by Kindle and Taylor in the Niagara Folio.

[5] Weller, *Jour. Geol.*, VII (1899), 483–88.

[6] *Geol. Atlas of the U.S., U.S. Geol. Survey*, Niagara Folio (No. 190), 1913, p. 109.

[7] Cf. Kindle, *Geol. Mag.*, Dec. 6, I (1914), 158–61.

[8] Cf. Grabau, *Bull. Min. and Metal Soc. Amer.*, VI, No. 2 (1913), 33–44.

and (8) the local downwarping along joint planes, to which this paper is directed.

The downwarping of certain layers near the top of the Lockport dolomite has been the subject of frequent reference, and illustrations of it have been copied and recopied. The structure was first described by Hall, who characterized it as concretionary.[1] Chamberlin and Salisbury[2] first called attention to the fact that the sag is along joint planes, an explanation which is concurred in by Hobbs,[3] but neither of these authors makes any comment regarding the period of deformation. This was first treated by Gilbert in 1905 in a paper of which we have only an abstract. After describing the structures he says[4] that he is not satisfied with Hall's characterization of them as concretionary, but that they were probably contemporaneous with the deposition of the strata and not subsequent to it.

The phenomenon has been described for the following localities: (1) Niagara limestone at Porter's quarry, Niagara Falls;[5] (2) Niagara limestone, Cook's quarry, near Lasalle, Niagara County, New York;[6] (3) Lockport dolomite, Niagara Falls: (*a*) in new railroad cutting; (*b*) in quarry 3 miles east of the city; and (*c*) in water channels temporarily exposed at the Dufferin Islands on the Canadian side;[7] (4) Lockport dolomite, Niagara Falls, old quarry 1½ miles east.[8]

The purpose of this paper is to show that such structures are essentially contemporaneous with the deposition of the strata, that they should be expected to occur where they do, that they are important, and that they have formed under essentially similar

[1] *Geol. New York*, Part 4 (1843), p. 94, Fig. 30.

[2] *Geology* (New York: Henry Holt & Co., 1904), I, 150, 151.

[3] *Earth Features and Their Meaning* (New York: Macmillan, 1912), p. 224, legend to Fig. 239.

[4] *Science*, N.S., XXI (1905), 224.

[5] *Geol. New York*, Part 4 (1843), p. 94, Fig. 30.

[6] Chamberlin and Salisbury, *Geology* (New York: Henry Holt & Co., 1904), I, Fig. 137, p. 151.

[7] Gilbert, *Science*, N.S., XXI (1905), 224.

[8] Kindle and Taylor, *Geol. Atlas of the U.S., U.S. Geol. Survey*, Niagara Folio (No. 190), 1913, Illus., III, Pl. XXIV.

conditions in rocks of Cambrian age where the evidence as to their early origin is conclusive.

In all of the Lockport localities that have been described the warped surface directly underlies till or marine clays. During the field season of 1915 a similar warped surface was discovered to be characteristic of the uppermost beds of the Middle Cambrian in British Columbia. These are dolomites and form the top of the Eldon formation. The basal beds of the Upper Cambrian rest directly upon this warped surface and, as if to yield further confirmation of the fact that the beds forming the top of the Eldon suffered prolonged exposure to the air and that such a condition continued during the period of deposition of the basal beds of the overlying Bosworth formation, the latter is full of mud-cracks, ripple-marks, and casts of salt crystals 2 inches or more in diameter.

The phenomenon was studied in the amphitheater north of Castle Mountain, and there is here no question that the warping was essentially contemporaneous with the deposition of the strata. It is interesting to note that the only known occurrences of this peculiar type of warped structure in both cases occur at the top of a dolomite overlain by shales with salt crystals and evidences of salinity. In the Lockport, Grabau[1] is of the opinion that the overlying Vernon suggests the accumulation of fine loess-like material, chiefly as wind-blown dust. This is of interest in connection with the theory of the eolian origin of the salt deposits of India discussed by Holland and Christie.[2] The bed immediately overlying the warped structure at the top of the Eldon is almost a pure dolomite, and the warped layers whose depressions it fills contain almost as little calcium carbonate. Grabau[3] describes the section between the Lockport and the Salina as composed of a "stratum of thin-layered bituminous accretionary limestone, forming flat, imbricating, shell-like domes" overlain by 2 feet of yellow impure limestone, which is in turn succeeded by the green shale forming the base of the Salina. In this paper on the early Paleozoic Delta deposits of North America, Grabau goes into the physical conditions

[1] *Bull. Geol. Soc. Amer.*, XXIV (1913), 490.

[2] *Rec. Geol. Survey India*, XXXVIII, Part 2 (1909), 154–86.

[3] *Bull. Geol. Soc. Amer.*, XXIV (1913), 491.

of Niagara time in great detail, but does not mention the warped surfaces. Likewise Clarke and Ruedemann, in their memoir on the Guelph,[1] do not mention these structures in their discussion of the conditions of life and sedimentation during the prevalence of this fauna. Writers agree, however, that there was a shallowing of the sea near the close of Lockport sedimentation and a gradual increase in its salinity and the magnesian content of its waters. Arguing from the extraordinary thickness of the Guelph molluscan shells, Kindle and Taylor[2] postulate the subjection of the bottom of the Silurian sea at this time to intense wave-action. Calvin[3] accepts the theory which had already been suggested by Hall that "at the close of the Niagara huge mounds and ridges were built on the bottom of the shallow Silurian sea, in part by the accumulation *in situ* of corals, crinoids, and molluscous shells, and in part by the drift of calcareous sediments under strong currents."

I am inclined to the opinion, and this appears to be corroborated by the position and physical character of the sediments involved, that the sagging of these beds, both those in the Eldon of British Columbia and those in the Lockport of New York, was largely caused by the gentle scour of water at a time soon after deposition. In each case the horizon of the warped structures is the locus of pronounced changes in the paleontologic record. In the Lockport the time was one of a prolonged emergence and marked the close of the Niagaran; in the Eldon it marks the close of the Middle Cambrian or Acadian and doubtless indicates a similar period of emergence at that time. Walcott, who did not, however, have the advantage of having seen the salt crystals of the Bosworth formation, says: "It is difficult to resist the conclusion that the 268 feet of shales forming the base of the Bosworth Upper Cambrian section were deposited in fresh or brackish water or on a river flood plain or delta such as Barrell describes so graphically in his studies of the *Geological Importance of Sedimentation*."[4] The warped structure at the top of the Middle Cambrian in British Columbia has been

[1] *New York State Museum, Mem. No. 5* (1903), 114–21.

[2] *Geol. Atlas of the U.S., U.S. Geol. Survey*, Niagara Folio (No. 190), 1914, p. 116.

[3] *Geol. Survey Iowa, Rept.*, 1896, p. 129.

[4] *Problems of American Geology* (Yale, 1915), p. 185.

observed, not only in the Castle Mountain section along the Canadian Pacific Railway, but in the Mount Robson section of the Grand Trunk Pacific 200 miles to the northwest. In each case it is followed by reddish-purple, green, and yellow shales, with ripple-marks, mud-cracks, and casts of salt crystals.

Salt crystals, previously known only from pre-Cambrian and post-Ordovician rocks, have been assumed, and rightly, to indicate arid conditions and more or less emergence. The peculiar type of downwarping described appears to be the natural result of the quiet subaërial exposure of recently consolidated dolomitic limestones under conditions of aridity. Whether or not the downwarping described is necessarily contemporaneous with aridity, it is certainly a feature due to subaërial exposure, and the probabilities are in favor of its formation at the time of the deposition of the strata rather than subsequently. This necessarily involves the assumption that the joints along whose channels the solution was localized came into existence very soon after the deposition of the strata and were relatively contemporaneous with the deposition of the beds. The evidence as to the early origin of the warped structures is so conclusive that we are justified in disregarding such coincidences as the immediate superposition, where so far discovered, of tills and clays upon the warped Lockport and such inferences as that, since the solution took place along joint planes, it must be comparatively recent. Have we not here rather a slight measure of the duration of the time-break in the deposition between the Middle and Upper Cambrian, and between the Niagaran and the Cayugan, and are we not justified in bearing in mind the principle of relatively contemporaneous consolidation and jointing in rocks?

THE WESTERN INTERIOR GEOSYNCLINE AND ITS BEARING ON THE ORIGIN AND DISTRIBUTION OF THE COAL MEASURES[1]

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While occupied with a study of the stratigraphy of the Mississippian formations of Iowa for the Iowa Geological Survey the writer has been attracted by the regular and nearly uniform gentle dip of these formations to the southwestward, and he has recently attempted to ascertain the age and significance of the deformation which gave rise to this. Investigation soon showed that the tilting was related to deformation over a wide area in southern Iowa, southeastern Nebraska, eastern Kansas, and northwestern Missouri which outlined a great southwestwardly pitching geosyncline in which the Coal Measures of the western interior coal field were deposited. The evidence is clearly in favor of the view that the movement took place, in part at least, during pre-Pennsylvanian time, as shown by the fact that the Coal Measures now rest upon trunkated Mississippian formations successively younger in age toward the southwest. This belted arrangement of the Mississippian deposits beneath the Coal Measures cannot be accounted for on the assumption that the distribution of the former is original, since the beds often consist entirely of nearly pure limestone up to their very boundaries and show no indications of shore facies.

That the geosyncline was shallow in early Pennsylvanian time is indicated by the fact that the maximum known thickness of the deposits of the Cherokee stage, which probably represents the time of greatest sea extension in this basin during the Pennsylvanian, is only 712 feet. At the present time, however, it attains a known depth of approximately 2,400 feet at McFarland, Kansas, and future drill records will probably show it to be considerably deeper than this to the southwest. The deepening is believed to have

[1] Published with the permission of the Director of the Iowa Geological Survey.

been brought about in part by subsidence during the post-Cherokee stages of the Pennsylvanian and in part by post-Pennsylvanian deformation. The data are not sufficient at present to warrant an estimate of the relative importance of each of the two. There is evidence that the original outlines and relations of the basin have been considerably modified by these later readjustments.

The magnitude and significance of the basin have been demonstrated by the construction of 100-foot contours on the base of the Coal Measures, from data furnished by the reports of the state geological surveys of Iowa, Missouri, and Kansas (Fig. 1). Contours showing the altitude of the base of the Coal Measures in Missouri have already been drawn by Hinds and Greene,[1] and these have been copied directly. Norton has also drawn a similar contour map for the southwestern and south-central portions of Iowa,[2] and this has been adopted with little modification.

The presence of this basin not only explains the great dissimilarity between the Coal Measures of this field and those of the eastern interior field, which were undoubtedly deposited in a distinct basin, but also explains the belted arrangement of the outcrops of the Pennsylvanian formations in Iowa, Missouri, and Kansas, where the younger members are approximately confined to the center of the basin, progressively older ones being exposed toward its margins.

There can be no doubt that this geosyncline exerted an important influence on sedimentation in this region during the Pennsylvanian. The work of Hinds and Greene in Missouri has furnished valuable data bearing on this point. Referring to the Cherokee deposits of that state they say:

> The Cherokee sea, advancing from the west or southwest, first invaded Missouri in the vicinity of Forest City, Holt County, and soon extended northeast as a long shallow arm through Worth, Harrison, and Mercer counties into Iowa. When about 150 feet of Cherokee sediments had been laid down the arm had broadened out to the southeast so as to embrace Buchanan and Platte counties, and a short time later Clay, Jackson, and Livingston counties. After the deposition of nearly 400 feet of material in the Forest City area the sea covered practically all of the western tier of counties, except Atchison, and

[1] *Mo. Bur. Geol. and Mines*, Vol. XIII, 2d Ser. (1915), Pl. 25.

[2] *Iowa Geol. Survey*, XXI (1912), 1101.

ILLINOIS
MISSOURI
NEBRASKA
KANSAS
MAP
SHOWING
WESTERN INTERIOR GEOSYNCLINE
DRAWN BY F.M. VAN TUYL AND H.S. KILLIAN
LEGEND
Structural contours on base of "Coal Measures"
Coastal deposits
Approximate boundary of "Coal Measures"

soon extended eastward into Henry, Johnson, Lafayette, Roy, Carroll, Linn, Putnam, and Adair. When the Bevier coal bed was formed, near the beginning of Allegheny time and after the deposition of 580 feet of material at Forest City, some sedimentation had already taken place in all the region now occupied by the main body of the Pennsylvanian and a fairly large area in which there are now only small patches remaining. The land area had been reduced to an island in southeastern Missouri, with a peninsula projecting into Pike and neighboring counties and a small part of a northern land mass in the extreme northwestern corner of the state. The western sea continued to advance eastward while an eastern sea occupying most of Illinois advanced westward. Probably by the end of Cherokee time the two seas had joined, submerging practically all of northern Missouri and possibly nearly all of southern Missouri also. No deposition appears to have taken place at this time in the extreme northwestern corner of the state, for the Nebraska City drilling shows less than 100 feet of Des Moines strata, probably of Pleasanton age.[1]

That these authors are justified in this conclusion is shown by a study of the thicknesses of the Cherokee in Missouri as listed by them.[2] Thus at Forest City in Holt County the thickness is 712 feet, while its average thickness in the counties to the eastward becomes successively less and less, viz., Livingston 450, Linn 260–310, Macon 175, Audrain 75. To the southeastward a similar relationship is shown, thus: Buchanan 530, Platte 555, Clay 460, Jackson 430, and Johnson 220–350 (see Fig. 2).

The influence of the basin upon the thickness and character of the post-Cherokee stages of the Pennsylvanian is not so obvious. The writer, after a careful study of all the available data, including deep-well and drill records from various parts of the area, has not been able to find any consistent variation in the thickness and lithologic character of the formations in tracing them from the center of the basin toward its margins. Nevertheless, the lack of relation between these deposits and those of the Illinois field suggests that the basin persisted and that its gradual though interrupted subsidence made possible the deposition of the Pennsylvanian formations of this province. It is believed that the original relations have been masked in large part by disconformities within the Coal Measures, several of which have been recognized, and by post-Pennsylvanian erosion, which has almost entirely removed the marginal facies of all the formations younger than the Cherokee.

[1] *Op. cit.*, p. 209.

[2] *Op. cit.*, pp. 39–40.

SIGNIFICANCE OF THE CHANNEL DEPOSITS

The channel deposits in the Coal Measures of Iowa and Missouri are very interesting in this connection in that they furnish

FIG. 2.—Map showing variations in thickness of Cherokee formation in Missouri. The influence of the basin is shown when this map is compared with that of Fig. 1.

corroborative evidence of the persistence of the basin in post-Cherokee time. With reference to such deposits in Missouri Hinds and Greene say:

> Among the most unique features of the Missouri Pennsylvanian are two long, narrow channels filled with sandstone and shale which have been eroded in Cherokee, Henrietta, and some Pleasanton strata in Johnson, Lafayette, Randolph, and other counties. Remnants of other channels have also been found in many parts of the Pennsylvanian area, and many more probably remain to be discovered as the net of detailed geologic work is spread over the state.
>
> The channels are of great scientific interest, for they must have been formed during an interval of more or less widespread emergence and erosion during

Pennsylvanian time. If, as suspected, the channel deposits are contemporaneous with certain sandstones and conglomerates of late Pleasanton age in north-central Missouri, this erosion interval occurred before the beginning of the Missouri epoch.[1]

The location and trend of the channels are shown on the accompanying map (see Fig. 1). The east-west channel has been designated the "Warrensburg" and the north-south one the "Moberly."

In describing these deposits Hinds and Greene state that—

the Warrensburg sandstone fills a channel about 50 miles long, extending from north of Lewis Station, Henry County, northward to the north bluffs of Missouri River. The sandstone belt, as at present exposed, has an average width of two miles, but just south of the Missouri widens to six miles. . . . .

The Moberly channel extends from South of Madison, in Monroe County, west to Chariton River south of Salisbury. Its length is nearly 40 miles and its average width less than 3 miles. The maximum depth shown in drill records is about 200 feet.[2]

With regard to the nature of the streams which gave rise to the channels the same authors express themselves as follows:

It is believed that the Warrensburg channel was made by water flowing from higher country on the Ozark dome, bringing with it sands and muds derived largely from early Pennsylvanian sediments. The Warrensburg stream was joined when it reached the present site of Missouri by the Moberly River descending westward from an Ozark peninsula in northeastern Missouri, and the united streams continued northward or northwestward to the open sea.[3]

Referring to the channel deposits presumably of a similar age in Iowa, Hinds and Greene say:

The Red Rock sandstone of Marion and Jasper counties, Iowa, lies in a channel 2½ to 3 miles wide that has been traced for 27 miles from Eagle Rock northeastward. This sandstone has a maximum thickness of 100 feet and has all the characteristics of the Warrensburg and Moberly sandstones.[4]

It will be noted that the trend of these old channels, both in Missouri and in Iowa, indicates that the drainage development during the temporary uplift in late Des Moines time was influenced by the geosyncline.

[1] *Op. cit.*, p. 91.
[2] *Ibid.*, pp. 95 and 97.
[3] *Ibid.*, p. 93.
[4] *Ibid.*, p. 94.

POST-PENNSYLVANIAN HISTORY OF THE BASIN

Subsequent to the deposition of the Paleozoic the Mississippi Valley region was uplifted. It seems probable that the geosyncline was deepened somewhat at this time and that secondary folds were developed. But the fact that the regularity of the basin has not been appreciably interfered with indicates that this secondary folding was not of great importance. Following this uplift the region underwent peneplanation. That the deposits occupying the geosyncline were peneplained by the beginning of the Upper Cretaceous is shown by the fact that the basal deposits of this age rest upon the beveled edges of the dipping formations, ranging in age from the Lower Mississippian on the marign of the basin in Iowa to the Permian in Kansas, at approximately the same elevation everywhere.

There is no evidence of further movement of the geosyncline during or since the Cretaceous apart from the regional uplift which brought the area to its present level. The present course of the Missouri River across the basin was obviously taken some time after the development of the peneplain.

A DECIMAL GROUPING OF THE PLAGIOCLASES[1]

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The accompanying diagram, which represents about half of the methods according to which the soda-lime feldspars have been grouped, reveals a surprising diversity of usage. Consistency, which undeniably would be of some advantage in the long run, is not likely to obtain until it is demonstrated that some particular scheme is better than all others. That this has not been done is perhaps because it has not been attempted; for, once the matter is given any critical attention, the most convenient and logical adaptation of current nomenclature seems rather easy to find.

The ideal plan should, first, accord with the modern doctrine that the plagioclases form a continuous series; schemes that imply a limited number of compounds (Nos. 1–3) must, therefore, be rejected.

Secondly, the intervals that separate the species in certain plans (Nos. 5, 8, 9) are needless, even when they imply no discontinuity. They then result in eleven-fold instead of sixfold division, compound names, like "andesine-labradorite," being applied to the intervals between the main species; but six terms, with qualifying adjectives, will suffice for as close discrimination as is worth while, and the awkward compound names may be reserved for feldspars that lie virtually at the junction of two species.

Finally, the division should be regular. The question arises here whether the names "albite" and "anorthite" shall be applied only to the pure soda and pure lime feldspars respectively, as in Zirkel's quite regular plan (No. 7), or whether they shall denote a certain range of composition. As absolutely pure end terms are mere abstractions, the answer to this question amounts to a choice between a fourfold and a sixfold division. It is only following universal practice to prefer the sixfold one. Now, there are but

[1] Published by permission of the Director of the United States Geological Survey.

two simple ways of dividing regularly a series of six parts: either to give all parts an equal range, or to give the end parts half the range of the others, which are mutually equal. The latter plan

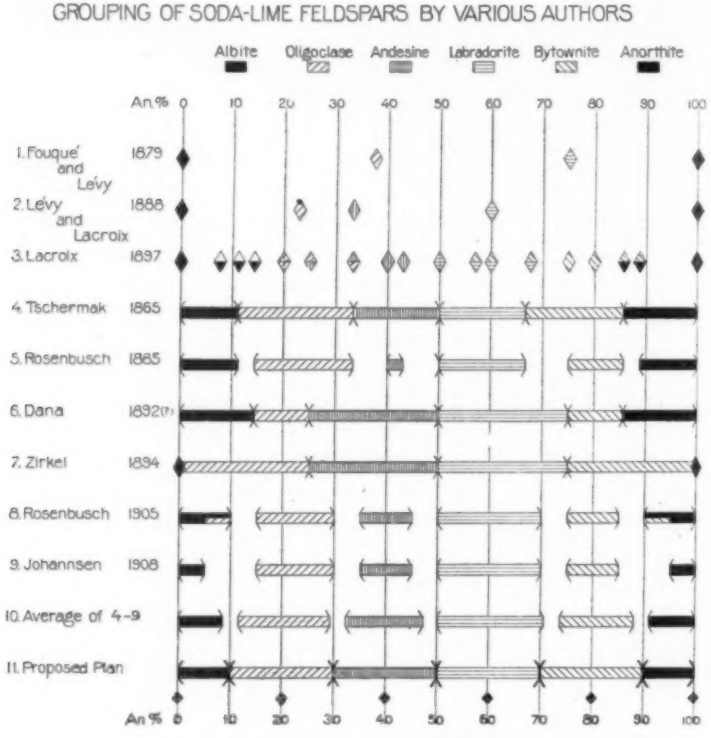

FIG. 1.—Sources of plans illustrated

1. F. Fouqué and A. Michel Lévy, *Minéralogie micrographique*, 1879.
2. A. Michel Lévy and A. Lacroix, *Les Minéraux des roches*, 1888.
3. A. Lacroix, *Minéralogie de la France et de ses colonies*, II (1897), 130.
4. G. Tschermak, "Die Feldspathgruppe," *Sitzungsberichte d. K. Akad.* Wien, L (1865), 566.
5. H. Rosenbusch, *Mikroskopische Physiographie*, etc., 2d ed., 1885 ("nach Tschermak").
6. J. D. and E. S. Dana, *System of Mineralogy*, 6th ed., 1892; also used by J. P. Iddings, *Rock Minerals*, 1906, and by F. W. Clarke, "Data of Geochemistry," *Bull. 330, U.S. Geol. Survey*, 1908.
7. F. Zirkel, *Lehrbuch der Petrographie*, 2d ed., 1894.
8. H. Rosenbusch, *Mikroskopische Physiographie*, 4th ed., 1905, Bd. I, 348.
9. A. Johannsen, *Determination of Rock-forming Minerals*, 1908.
10. Average of 4–9.
11. Decimal grouping.

seems the more logical as well as the more accordant with usage. It leaves equal spaces between the several types; for, if the most typical andesine is average andesine, the most typical albite is pure albite.

It is therefore proposed that the divisions be placed, as in Diagram 11, where the ratios of anorthite to albite are $\frac{1}{10}$, $\frac{3}{10}$, $\frac{7}{10}$, and $\frac{9}{10}$.

The questions of priority and of average practice have thus far been left in the background. If priority determined preference, Tschermak's plan (No. 4) should be preferred; and the belief seems general that his plan is most in use. But, rather oddly, the scheme that currently passes for Tschermak's is a modification thereof by Rosenbusch (No. 5). The scheme proposed in the present note resembles Tschermak's more closely than does any other. Still more closely does it resemble the scheme (No. 10) deduced by averaging the ranges of species in Diagrams 4 to 9. The slightest alteration that will regularize this "average" plan and close its gaps produces the decimal grouping.

A decimal grouping goes naturally with centesimal symbols, of which the most-used form is Ab_nAn_{100-n} (e.g., $Ab_{40}An_{60}$, or $Ab_{25}An_{75}$); these, moreover, present certain practical advantages. They give, more quickly than those like Ab_2An_3 and Ab_1An_3 a definite idea of relative composition—which is merely saying that decimals are more easily subtracted than common fractions. The decimal co-ordinates, too, upon which extinction-angle curves are plotted, indicate the composition corresponding to a given angle in percentages, which it is a needless trouble to reduce to a fraction of a small denominator. Since in such curves the anorthite increases toward the right, it is by the percentage of anorthite, rather than by that of albite, that the composition is naturally measured. Therefore, a symbol such as An 60%, or $An_{.60}$, which indicates this percentage alone, conveys the essential information more economically than the symbol $Ab_{40}An_{60}$; the former's greater convenience, however, is possibly outweighed by the greater currency of the latter.

STUDIES FOR STUDENTS

A CLASSIFICATION OF BRECCIAS

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Few geologic structures so lend themselves to diverse interpretations as the beds of broken rock called breccia. Example after example might be cited of breccias of Europe and America which have been differently explained by different students during the last half-century and as to whose origin no consensus is yet attained. This diversity of opinion seems partly due to the large number of processes by which rocks are broken up, assembled, and cemented into breccia, and to the fact that breccias may offer no very obvious and indisputable evidences of the method of their making. Diagnosis generally requires the use of multiple working hypotheses and may proceed chiefly by the process of elimination. For this reason a genetic classification which the writer has prepared in connection with a field study of certain breccias affecting the Wapsipinicon stage of the Devonian of Iowa may prove of interest to students of these structures.

The diagnosis of a breccia requires the close observation of its most intimate characteristics as well as of its associations with the adjacent rocks. The matrix may be like or unlike the fragments lithologically. It may be a chemical precipitate, a sedimentary deposit, or the detritus of attrition. In volume it may be greater or less than the fragments—interstitial, merely filling the spaces between the fragments closely packed, or preponderant, forming the larger part of the rock-mass in which the fragments are sporadic.

The fragments may be of any size, from huge blocks down to chipstone. Lithologically they may be similar or dissimilar, according as they result from the fragmentation of a homogeneous rock-mass or from that of heterogeneous beds. They may be sharply angular, more or less rounded by attrition in earth movements, or even in part water-worn and approaching a conglomerate.

They may be local in derivation, produced by the breaking up *in situ* of a terrane, or they may have suffered transportation from distant sources. They may be simple or of complex and brecciated structure, the result of an earlier brecciation.

Breccia may form a mass entirely destitute of planes of bedding. When bedded in a distinct stratum it may be classified as *endostratic*.

A *crackle breccia*, representing incipient brecciation, is one whose fragments are parted by planes of fission and have suffered little or no relative displacement. The fragments match along their apposed sides. The matrix is confined to the seams and is commonly a chemical deposit.

A *mosaic breccia* is one whose fragments have been largely but not wholly disjointed and displaced. The system of continuous cracks of the crackle breccia has been destroyed, but more or less of the fragments still match along adjacent surfaces and show that they are consanguineous parts of once unbroken laminae or larger beds. The term suggested is not a happy one, yet these breccias may recall some ill-preserved mosaics of ancient ruins. The matrix is confined to the seams and to the wider and irregularly shaped interstices.

A *rubble breccia* is one in which no matching fragments are parted by initial planes of rupture. The fragments are close-set and in touch.

A *breccia of sporadic fragments* is one in which the fragments are imbedded in a preponderant matrix like plums in a pudding. It recalls the term "plum-cake rock," applied by the quarrymen of North England to the breccias of their region. In his study of the Permian Midland breccias of England, King[1] distinguishes an endostratic breccia of this class by terming it "breccia sandstone," thus emphasizing the bedded matrix rock.

Breccia may be fossiliferous. Fossils may be restricted to the fragments or to the matrix or may be found in both. Fossils of the matrix may themselves be fragments. Brecciation may be practically contemporaneous with the involved deposits. Such are the *intraformational breccias* of Walcott. In certain classes

[1] W. W. King, "Permian Conglomerates of the Lower Severn Basin," *Quar. Jour. Geol. Soc. London*, LV (1899), 105.

of breccia the matrix is of the same age as the fragments. In other classes it is younger, and in still others it may even be supplied by an older bed.

Breccia may be of slight extent and evidently due to local causes. On the other hand, some of the most perplexing breccias are regional and demand causes equally widespread in operation.

According to the conditions under which they accumulate, breccias may be classified as *subaërial*, *subaqueous*, or *endolithic*, formed within the lithosphere, the earth's crust.

In classifying breccias genetically it will be remembered that the making of a breccia involves, or may involve, three distinct processes—fragmentation, assemblage of the fragments, and cementation by the introduction of the matrix. In any given breccia all of these processes may belong to the same or to different categories. The genetic classification may have in view either fragmentation, as in crush breccias, or assemblage, as in several other types.

Subaërial breccias, in which both fragmentation and assemblage are above ground, may be classified as follows:

Residual breccia	Bajada breccia
Talus breccia	Glacial breccia
Rock-glacier breccia	Volcanic breccia
Landslide breccia	

Residual breccia.—This type is formed of the angular débris of the waste mantle. It has been designated as "basal breccia,"[1] since it corresponds in position to a basal conglomerate. But all subaërial breccias covered and preserved by the deposits of a transgressing sea may correspond equally well to basal conglomerates, so that some designation seems preferable which suggests the residual origin of this specific kind.

Residual breccias develop especially on Karst topographies where the limestone of the country rock contains cherty beds. Under long denudation the surface with its characteristic sink-holes and closed valleys comes to be covered in places to some depth with breccia of sharp-edged chips of flint, and this by submergence may be incorporated into the sequence of the geologic formations.

[1] W. S. Smith and C. E. Siebenthal, *U.S. Geol. Surv., Geol. Atlas*, Joplin Folio (148), p. 9.

The residual breccia of the Joplin district of Missouri has been described by Winslow,[1] Smith and Siebenthal,[2] and others. The breccia-producing rocks are Mississippian limestones rich in chert. At the close of the Mississippian the region was uplifted and, under long subaërial erosion, developed a typical Karst topography mantled with angular cherty waste. During early Pennsylvanian times the area was deeply submerged; the Carboniferous sea transgressed, but without either leveling the relief or assembling and rounding the residual cherts. The matrix is largely supplied by the sea-clays of the Cherokee formation. The residual breccia thus formed suffered further changes. Solution of the underlying limestone has caused the breccia to founder, producing complex brecciation and intermingling blocks of the country rock. Groundwater has also introduced a matrix of lead and zinc ores and jasperoid silica.

Talus breccia.—Accumulating at the foot of cliffs, from fragments broken off by frost and temperature changes, talus breccia is a rubble of sharp-edged fragments, wedge-shaped in radial section, and quite devoid of bedding. Stratification may be rudely simulated, since slabs and other unequiaxed blocks creeping and sliding down the slope come to rest with their longer axes parallel with the surface. Owing to greater inertia, the larger blocks may gather at the base. Small fragments prevail, but blocks of some considerable size may be supplied by local sapping. The matrix (the finer material derived from the weathering of the cliff and of the talus) is interstitial and lithologically identical with the fragments. Some of the matrix, however, may be foreign—dust and sand brought in by wind, humus of a soil cover, and travertine deposited by springs issuing from the cliff's base.

Talus breccias are local and extremely limited in width. Even under an arid climate favoring the perpetuation of cliffs, even in the hamada desert, where long lines of marching cliffs form the high risers for the broad steps of rock plateaus, talus accumulations are rapidly consumed by deflation and are but a few rods wide. The material is local and there is no zonal arrangement of fragments of different lithologic kinds.

[1] Arthur Winslow, *Missouri Geol. Surv.*, VII (1894), 464 f. [2] *Op. cit.*, p. 9.

An example of a talus breccia is described by Wilson[1] as occurring at the base of a cliff of Keweenawan sandstones covered by a sheet of ancient diabase.

Rock-glacier breccia.—A subspecies of talus breccia is that produced by rock glaciers, talus glaciers, or rock-streams, as they are variously known.[2] Talus may be very rapidly produced where the wedgework of frost is especially efficient, as in cold climates, on the lofty walls of cirques composed of rock that favors fragmentation by close jointing, or other structures. Under the urge of its own weight and that of the expansion of interstitial ice talus creeps forward from the feeding cliff in long tongues of waste which in shape somewhat resemble glaciers. Rock-glacier breccia differs from talus breccia only in its greater extension normal to the cliff, in the movement of the material to greater distances and with very gentle slopes, and in the fact that unequiaxed blocks may be expected to be found set at all angles, owing to the movement of material *en masse*.

The famous limestone breccias of Gibraltar, described by Ramsay and Geikie,[3] are attributed to this class. These breccias occupy wide tracts about the base of the Rock of Gibraltar and reach a thickness of at least 100 feet. Their slope in places does not exceed two or three degrees. The fragments are almost invariably quite angular. They vary in size from grit up to blocks 12 feet or more in diameter, and are distributed without regard to size and shape. They are no larger at the base of the cliffs than on the outskirts of the formation. The matrix is earthy and cements the breccia into firm rock. The authors cited attribute fragmentation to the work of frost under far severer climatic conditions than now obtain. The assemblage of the breccia by gravity in ordinary talus is negatived by the extent and slope and apparently by the set of the fragments. The angularity of the fragments, their size, and their lack of sorting preclude the theory of transportation

[1] A. W. G. Wilson, "Trap Sheets of the Lake Nipigon Basin," *Bull. Geol. Soc. Am.*, XX, 207–9.

[2] Whitman Cross and Ernest Howe, *U. S. Geol. Surv., Geol. Atlas*, Silverton Folio, p. 25; S. R. Capps, "Rock Glaciers in Alaska," *Jour. Geol.*, XVIII, 359–75.

[3] A. C. Ramsay and James Geikie, *Quar. Jour. Geol. Soc. London*, XXXIV, 505–41, 1878.

by torrential streams upon detrital slopes. It is concluded that heavy trains of débris saturated by meltings of thick snows have moved *en masse* down the steep slopes and out over the lower grounds below. The junior author reaffirmed this theory in 1881 and compared the breccia directly with the talus glaciers of the Rocky Mountains.[1]

A matter perhaps less satisfactorily explained is the frequent brecciated aspect of the undisplaced limestone of the Rock of Gibraltar. In the words of the authors cited, "In many places the Rock looks as if it had been smashed up *in situ*, the broken fragments having been subsequently consolidated by infiltration." The authors prove that the shattering is not due to faulting, and attribute it to frost. The fractures recall, however, those of the country rock of the landslide area of the Rico Mountains, referred by Cross[2] to prehistoric earthquakes of exceptional violence. Indeed, the features of the Gibraltar breccias as described by Ramsay and Geikie are not inconsistent with an origin in landslides, which also move out over gentle slopes and carry large fragments to the outer limits.

Landslide breccia.—Breccias of this class owe fragmentation in large measure, and assemblage wholly, to the force of gravity. In *rock-falls* the movement is sudden and violent, and the rock is shattered to pieces by successive impacts. Rock-fall breccia is a chaotic mixture of blocks, large and small, set at all angles and sharply angular. In the few seconds of the tremendous downrush of perhaps millions of tons of rock, the fracture of the masses to smaller and still smaller fragments and their crush to powder go on so rapidly that comparatively little opportunity seems to be given to the rounding of edges by attrition. The matrix consists of chinkstone and pulverized material and may embrace a contribution of soils and subsoils swept up by the rock-torrent.

Large rock-falls on steep slopes obtain sufficient momentum to carry them a considerable distance over gentle and even reversed gradients at the mountain's base. In the Elm rock-fall of 1881

[1] James Geikie, *Prehistoric Europe* (London, 1881), p. 219.

[2] Whitman Cross, "Geology of the Rico Mountains, Colorado," *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 149.

the landslide mass, after reaching the foot of the mountain, poured down the level valley floor for nearly a mile, covering it over its whole width to a depth of more than 30 feet.[1] The section of a rock-fall breccia taken normal to the cliff therefore resembles that of the rock-glacier. No marked difference in the size of fragments in different parts of the area covered has been recorded, so far as the writer is aware. In the breccia formed by the landslide at Frank, Canada, in 1903, described by McConnell and Brock,[2] large rocks are said to be common everywhere.

In rock-fall breccias, fragments are of local derivation and of a limited number of kinds of rock. No zonal arrangement is possible in a single slide; but where repeated falls occur, the earlier bringing down material from higher horizons on the mountain and the later falls material from lower terranes, zonal arrangements both vertical and horizontal may result. Thus Howe[3] explains the zone of rhyolite which forms the outer rim of the Pierson Basin rock-stream in Colorado, while the center of the mass consists of fragments of andesite of a lower volcanic series.

In *rock-slides* the movement is gradual and repeated. The displaced mass, therefore, is not so completely broken up as in the rock-fall, nor does it come to cover so large an area, except under special conditions. No type of breccia contains such large blocks as this. While the largest blocks of the Frank rock-fall measured 40 feet, blocks 300 feet in diameter occur in the Rico rock-slides, and in the profounder displacements of the adjacent Telluride quadrangle one block of more than two miles in length has been described.[4] On the north side of the Grande Ronde River, Idaho, the Columbian lavas supply slidden blocks half a mile in length.[5] The breccia of rock-slides is characterized by the confused relations of the slipped blocks, their varying dip

[1] Sir W. M. Conway, *The Alps from End to End* (Westminster, 1895), 3d ed., p. 246.

[2] R. G. McConnell and R. W. Brock, *Ann. Rept. Dept. of the Interior, Canada*, 1903, Part VIII.

[3] Ernest Howe, "Landslides in the San Juan Mountains, Colorado," *U.S. Geol. Surv., Prof. Paper 67*, p. 34.

[4] Whitman Cross, *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 146.

[5] I. C. Russell, *U.S. Geol. Surv., Water Supply Paper 53*, p. 76.

and strike, their fissured and shattered condition, and their merging in places into rubble breccia of small fragments due to the breaking up of the blocks either by the force of the original slide or by that of later movements. A diagnostic may be found in the inward dip of the blocks, as noted by Russell.[1] Owing apparently to friction with the surface, the sliding blocks tend to rotate backward on axes normal to the slope and thus come to rest with a marked dip toward the cliffs from which they were derived. On the other hand, blocks creeping down talus maintain a dip parallel with the slope. The upper surface of both rock-fall and rock-slide breccias is hummocky, but this feature will hardly be preserved excepting where the landslide fell into deep water.

Bajada breccia.—The rugged mountains of arid regions are commonly fringed with wide slopes of rock-waste called bajada. Like those of talus, the fragments of the bajada have been detached by mechanical weathering. But unlike other subaërial breccias, the bajada has been aggregated largely by intermittent streams. Its fragments have been more or less water-worn. It forms an imperfect breccia and yet is far from being a typical conglomerate of well-rounded pebbles. The streams which build the bajada have certain peculiarities which greatly lessen the wear on the stones they carry. The long accumulated waste on the mountain slopes swept down by spasmodic rains loads so heavily the temporary streams of the barrancas that they have been designated as mud-flows.[2] In the washes and on the lower unchanneled slopes of the bajada the viscosity of the flow is further increased by absorption of the water by the thirsty sands. In the moving mass of the mud-flow, stones such as are carried in mountain torrents of humid climates as the bottom load and dashed against one another and the stream bed are here intermingled with the finer waste held in suspension, and are thus protected from mutual abrasion. Hence pebbles remain imperfectly rounded even to the outer edge of the bajada slope.[3]

[1] I. C. Russell, "Geology of the Cascade Mountains in Northern Washington," *U.S. Geol. Surv., 20th Ann. Rept.*, Part II, p. 19.

[2] For a graphic description of a mud-flow in the Himalayas see Sir W. M. Conway, *Geog. Jour.*, II (1893), 291.

[3] R. D. Oldham, *Quar. Jour. Geol. Soc. London*, L (1894), 469.

Unlike all other subaërial breccias, the bajada is stratified, and unlike that of marine and ordinary fluviatile conglomerates, the stratification is imperfect. The bedding is often local and ill-defined. Unsorted beds pass both vertically and horizontally into those well sorted. All this follows from the nature of the building-streams. Leaving the barrancas of the mountains and debouching on the gentler slopes, they suffer a sudden arrest of velocity as well as diminution of volume by the absorption of their waters. These checks are often enough to cause them to throw down their load, fine and coarse alike, with little or no sorting. The attitude of unequiaxed fragments of mud-flows on bajadas has not been sufficiently observed. It may be inferred from the method of their carriage that they will not always take the position of repose and that even flat stones may be left at any angle.

A bajada breccia is wedge-shaped, but on a larger scale than that of talus. Furthermore, there is a gradual decrease in size and angularity of the material in passing from the thick to the thin end.

The matrix of the bajada consists of the finer stream-wash and of dust and sand contributed by the wind. Beds of rubble breccia with interstitial matrix pass into endostratic breccias of predominant matrix and sporadic fragments. A characteristic matrix is a chemical deposit of lime carbonate by calcareous evaporating water. As in the Tintic mining district, Utah,[1] the material may thus be cemented into compact rock in which roofs and walls of deserted tunnels remain standing for years untimbered. The limy matrix may whitewash the pebbles and, by filling the interstices, form beds of caliche.

Dry climate conditions are indicated further by the absence of carbonaceous deposits and by the complete oxidation of iron compounds, the interfingering of playa clays about the outer margin, and, under extreme aridity, the association of beds of salt and gypsum in the centers of the bolsons. Wind-carved pebbles may be found, and beds of the millet-seed sand of the desert. The presence of well-rounded sand grains in a breccia, however, is a criterion to be used with intelligent caution. Desert sand once

[1] G. W. Tower and G. O. Smith, *U.S. Geol. Surv., 19th Ann. Rept.*, Part III, pp. 668–69.

shaped retains its form indefinitely. Thus the St. Peter sandstone, whose grains were originally ground under desert winds, was spread by the Ordovician sea, and again supplied the material for the Sylvania sandstone of Michigan. Either of these sandstones could furnish desert sand to breccias of several different types.

Bajada breccia is of local derivation; far-traveled stones from distant sources are not expected, yet the extent and complexity of the feeding-mountains may give the breccia great lithological heterogeneity. Ancient breccias are not necessarily associated with the buried mountains or uplands which supplied their waste. Such elevations may have been destroyed in the building of the bajada or by later denudation.

The Permian breccias of the Midlands, England, are now commonly regarded as of bajada origin.[1] They occur in rudely stratified, wedge-shaped masses, some more than 200 feet thick at one end and thinning out within four to eight miles. Beds of breccia are interstratified with current-laid sandstone and with marl, into which they graduate both vertically and horizontally. The fragments embrace a large variety of rocks and are now considered of local derivation. They are angular and subangular, more or less water-worn, but are never well rounded. Half a foot is a common measure of their size where they are largest. The matrix is calcareous or sandy.

Certain coarse breccias, intercalated with thin sandstone layers, in the Esmeralda formation of Nevada have been classified as detrital-slope breccias by Turner.[2] Examples well known to American students are the bajada breccias of the Newark formation.

Glacial breccia.—Subaërial glacier deposits are certainly to be classified as breccia, but their characteristics are so well known and so easily recognized, as a rule, that no description is considered needful.

[1] R. D. Oldham, *Quar. Jour. Geol. Soc. London*, L (1894), 463–70; W. W. King, *ibid.*, LV (1899), 97–128; T. G. Bonney, *ibid.*, LVIII (1902), 185–203.

[2] H. W. Turner, "Geology of Silver Peak Quadrangle," *Bull. Geol. Soc. Am.*, XX, 245.

Volcanic subaërial breccia.—Volcanic breccias laid in open air include:

1. Flow breccia, in which unrounded fragments have become incorporated in flowing lava, either from its frozen and broken crust or from material, volcanic, residual, or of other origin, overridden by the advancing stream.

2. Tuff breccia, made up of the fragmental products of explosive eruptions. The matrix consists of the finer materials of the eruption and in some instances has been washed in by mud-flows. Or the matrix may be formed by gangue and ore stuffs deposited in the interstices by heated waters. Tuff breccias often include fragments of the country rock torn from the sides of the duct below the base of the volcanic cone.

Subaqueous breccias.—Breccias accumulated under water may be divided into three general classes with the following subdivisions:

1. Breccias of subaërial fragmentation
   a) and *b*) Subaqueous talus and landslide breccia
   c) Raft breccia, deposits from rafts of ice (iceberg or ice floe), trees, or seaweed.
   d) Desiccation breccia
   e) Subaqueous volcanic breccia
2. Breccias whose fragmentation is the work of aqueous agencies or of agencies working in water
   a) Shoal breccia
   b) Reef breccia
   c) Beach breccia
   d) Tide-glacier and shore-ice breccias
3. Breccia whose fragmentation is due to internal stresses
   a) Glide breccia due to overload, earthquakes, deformation, undercut

Talus and landslide subaqueous breccias.—These two varieties may be taken up together because of certain common features. Both consist of local beds of angular fragments from near-by sources, intercalated between younger sedimentary strata. Suitable topographic conditions for the formation of each are found in the fjords and rias of a rugged coast and in mountain lakes, especially Chelans, lying in oversteepened glacier troughs. The matrix is partly of the same material as the fragments and partly of infil-

trating sediments. It is generally interstitial, in contrast with the preponderant matrix of raft breccias, but about the margins blocks projected farthest may be found sporadic.

Talus and landslide breccias may be discriminated from each other by their characteristic profiles—the even and smooth slope talus and the hummocky surface of the landslide—by the longer extension of the landslide from the parent cliffs, and, in the following example, by the landslide tearing up the sediments of the sea-floor over which it moves and mingling them with its own débris.

The very interesting Jurassic breccia of the Ord, on Moray Firth, Scotland, is pretty certainly due to a landslide fallen into the sea.[1] The strata among which the breccias are imbedded consist of finely laminated shales with occasional thin seams of limestone. Hence the water in which they were laid was quiet, unvexed by powerful waves or currents. The littoral fossils—ammonites, corals, etc.—show that the deposits are marine and indicate the close proximity of the shore. This is confirmed by numerous remains of cycads, ferns, and conifers apparently drifted in by rivers. Both fauna and flora prove the warmth of the climate and forbid the assumption of an ice raft as the means of transportation. The breccia is contemporaneous with the Jurassic beds in which it lies, but it is not intraformational, since its fragmental material is derived from the Old Red Sandstone which occurs in the immediate vicinity. The fragments vary in size from chipstone to blocks 10 feet in diameter. The majority are sharply angular, some show signs of attrition on the edges, and not a few, especially those of smaller size, are completely rounded. They are heaped together in the wildest confusion. The upper surface of the breccia beds is irregular, and the strata deposited upon it show the influence of its projections. The breccias vary in thickness from a foot or two to 50 feet. The matrix is fossiliferous with contemporaneous Jurassic fossils in a more or less comminuted condition. In places are found numerous masses of Jurassic reef-building coral torn from their bases and heaped in all positions among the débris.

[1] J. W. Judd, "The Secondary Rocks of Scotland," *Quar. Jour. Geol. Soc. London*, XXIX (1873), 187–95; J. F. Blake, "On a Remarkable Inlier among the Jurassic Rocks of Sutherland," *ibid.*, LVIII (1902), 290–310.

All these phenomena are explained by landslides descending from the steep slopes of Old Red Sandstone hills or mountains into the quiet waters of a Jurassic fjord or ria and depositing on the even-layered silts the tumultuous beds of breccia. The débacle would sweep up rounded pebbles from the beaches, tear corals from their bases, crush shell banks in the estuary, and mingle their débris with the fragments of the slides. That earthquakes were the cause of these great rock-falls is suggested by the contemporary sandstone dikes found in the district.[1]

It may be added, if only in illustration of the diverse interpretations held of breccias, that Murchison[2] described these breccias as due to crush incident to the upheaval of neighboring granite. Blake[3] argues the deposit of an ice foot. Huddleson, in the discussion of Blake's paper, postulates ocean currents strong enough to tear up masses of corals and to gather and distribute old shore accumulation of talus, although ocean currents, even if powerful enough to transport the immense blocks of the breccia without wear of edges, are not so paroxysmal as to heap them in the midst of the fine silts of quiet water. Judd[4] recognizes the cataclysmic nature of the formation and suggests very tentatively river-floods of the most violent character. Yet the floods of a river cannot be expected so to maintain their energy on entering the ocean as to deposit their bottom load in water of considerable depth and to mingle it with detritus torn from the ocean floor. The momentum of the rock-fall would seem to be the only force capable of the work, and this origin is advanced by Woodward[5] and by Teall[6] in the discussion of Blake's paper.

Raft breccias.—In breccias of this class the fragments have been transported in such a way as to escape wear *en route*. Angular fragments of such soft rocks as shale and talcose, schists and limestone, brought unworn from distant sources, prove that the carriage was upon the surface of the ocean, and not by wave and current along the ocean floor. Further evidence of surface trans-

[1] H. B. Woodward, *Quar. Jour. Geol. Soc. London*, LVIII (1902), 206.

[2] *Transactions Geol. Soc. London*, Ser. 2, Vol. II, Part II, p. 293.

[3] *Op. cit.* [4] *Op. cit.* [5] *Op. cit.*

[6] *Quar. Jour. Geol. Soc. London*, LVIII (1902), 205.

port should be looked for in disturbances in the bedding of the inclosing strata. Laminae beneath the larger stones may be bent down, and the succeeding laminae may show the influence of the projecting blocks, thus proving that the fragments were dropped through some depth of water. Confirmation has been found in the position of fragments with the heavier ends downward.

Raft breccias are endostratic and the fragments are sporadic. There may also be an irregular distribution of them—in places a huddle of fragments where the unloading of the raft was sudden. Some blocks may be quite too large for wave and current carriage.

Rafts capable of transporting the material of breccias are either of ice or of vegetation. Ice rafts include both icebergs and shore ice in the form of floes, or of the ice-foot.

Iceberg breccia.—Since the iceberg is detached from the tide glacier, iceberg breccia is composed of the material of the ground moraine. In a larger or smaller proportion the fragments prove their derivation by their subangular form and striated faces. A considerable lithologic variety is to be expected, since the parent glaciers usually drain a large extent of country. Transport from distant sources has long been looked upon as evidence of iceberg carriage, since icebergs drift farther than other rafts.

In weighing the evidence of iceberg breccia, and of glacier breccia as well, it is often necessary to discriminate glaciation of pebbles from slickensides by earth movements which affect the mass of the formation. In favor of glaciation is the incrustation of planed or striated surfaces by marine organisms, such as serpula or shells, since these surfaces must have been produced before the deposit of the pebbles in the breccia beds.[1]

Striae may be considered "rutsch striae" produced after the deposit of the breccia under the following conditions: (1) when they occur on matrix as well as pebbles; (2) when they are found on different planes below the surface of the pebbles; (3) when they affect traceable planes or zones of shear; (4) when the striae of different pebbles in the same plane run in the same direction and

[1] I. C. Russell, "Second Expedition to Mt. St. Elias," *U.S. Geol. Surv., 13th Ann. Rept.*, p. 25; W. J. Sollas and A. J. Jukes, "Included Fragments of the Cambridge Upper Greensand," *Quar. Jour. Geol. Soc. London*, XXIX (1873), 11–15.

correspond in direction with earth movements recorded in adjacent strata; (5) when the number of striated pebbles in different parts of the breccia varies directly with the amount of shear; (6) when the striae on faulted pebbles end at the fault plane; (7) when the striated surface is covered with films deposited from solution. Several of these diagnostics are mentioned by Marr[1] as characteristic of scored pebbles having the form of glacial bowlders in an English breccia. Tectonic breccias often display slickensided blocks,[2] but they are hardly liable to be confounded with glaciated pebbles. It may be added that the proportion of glaciated pebbles in iceberg breccias may be exceedingly small in comparison with that in the drift-sheets of far-traveled continental glaciers.

Iceberg breccia, as well as any other, may be sheared after its formation. In this case neither slickensides nor glaciation can be used to disprove the other process. A dual origin seems to be indicated in scored pebbles of some of the Permian breccias of England, but there are students who claim that they are due to earth movements only.

Shore-ice breccias.—In arctic regions shore ice often receives a load of angular waste, and, drifting along the coast or out to sea, desposits it as breccia amid the sediments of the ocean bed.

The ice-foot, described by Feilden and De Rance[3] as having its origin chiefly in snows drifted into water offshore, receives the waste of the talus slopes at whose base it lies. Ice floes along shore also obtain a load of similar débris tobogganing out from talus slopes and falling upon the floes from sea-cliffs. Shore ice may also carry rounded beach pebbles frozen to its base and glaciated pebbles shaped by the grinding of ice pans on shelving shores in storms and under the action of the tide.

The Quebec group of the Ordovician of Canada contains breccias explained by Sir J. William Dawson as early as 1833 as due to shore

[1] J. E. Marr, "Notes on a Conglomerate near Melmerby," *Quar. Jour. Geol. Soc. London*, LV (1899), 11–13.

[2] E.g., the Wapsipinicon breccias of Iowa, W. H. Norton, *Iowa Geol. Surv.*, IX, 447–48.

[3] H. W. Feilden and C. E. de Rance, "Geology of the Arctic Coasts," *Quar. Jour. Geol. Soc. London*, XXXIV (1878), 563–66.

ice.[1] These breccias are very irregular in their distribution and vary rapidly and greatly in their thickness. The fragments are of Cambrian limestone and of the lower limestones of the Quebec group. "The only means of explaining these conglomerates seems to be the action of coast ice . . . . which seems to have had great reefs of limestone, probably in the area of the Gulf of St. Lawrence, to act upon and to remove in large slabs and bowlders, piling these up on banks to constitute masses of conglomerate." Walcott also postulates floating ice in the absence of any other explanation in accounting for bowlders in certain intraformational conglomerates, saying: "No other explanation occurs to me that will account for the transportation of a bowlder from the shore line and the placing of it upon the sea-bed so as not to disturb to any marked degree the sediments then accumulating."[2]

The bowlder beds of the Talchir group of India are attributed to ice rafts by Oldham.[3] Sporadic bowlders from distant sources and reaching a maximum diameter of 15 feet are distributed with extreme irregularity in distinctly stratified shales and sandstones. Large numbers occur within limited tracts, but over many square miles of the area they are quite absent. Where the sedimentary matrix is laminated, the laminae bend down beneath and arch over the included blocks. As the fragments are far too abundant and widespread to have been carried by rafts of vegetation, floating ice remains the only possible vehicle. This inference is confirmed by the presence in two localities of striated pebbles, although most of the fragments are distinctly water-worn. The various phenomena of the Talchir beds point to their accumulation in large inland water bodies covered with ice in winter, to which torrential streams led down steep valleys and to which glaciers locally descended.

Tree-raft breccia.—Uprooted trees, drifted down to sea on river-floods, may carry for some distance out from shore angular stones

[1] Sir J. W. Dawson, "On the Eozoic and Paleozoic Rocks of the Atlantic Coast of Canada," *Quar. Jour. Geol. Soc. London*, XLIV (1888), 809–910, quoting an earlier paper.

[2] C. D. Walcott, "Intraformational Conglomerates," *Bull. Geol. Soc. Am.*, V, 197.

[3] R. D. Oldham, *Geology of India*, 2d ed., pp. 157–60.

of the waste mantle and of the weather-broken rocks beneath, firmly held entangled in the meshes of their roots. The fragments may be expected to be smaller than those of the ice raft. Fine waste is absent from the breccia, since it is soon washed out of the interlacing roots of trees when immersed in river or sea. Since the fragments are derived from the zone of weathering, decomposed and etched surfaces and weather-rounded edges may be looked for, especially in fragments made of the more soluble rocks.

Seaweed breccia.—The buoyant power of seaweeds and the tenacity with which they adhere to rock are well known. They are thus able to transport stones so small that they would readily escape from the roots of floating trees. At the Orme's Head, North Wales, angular fragments of limestone have been found attached to the roots of Laminaria.[1] The stones which seaweed commonly carry are the well-worn shingle of the pebble beach. But angular stones may be transported by them when fragments are broken by the battering of waves from the rocky reefs on which seaweeds grow.

A pudding breccia occurring in one or two localities near Dublin, Ireland, has been attributed to tree rafts by Jukes[2] and to carriage by seaweed by Ball,[3] although earlier observers had invoked rafts of floating ice. The matrix is highly fossiliferous, encrinital, carboniferous limestone. The fragments, sharp-edged, sporadic, small, are of granite and metamorphic rock outcropping in the neighborhood. The small size of the fragments lends some weight to seaweed as the transporting agent.

Desiccation breccia.[4]—Surface layers of unconsolidated fine-grained sediments, such as clay or limy mud, when exposed to the air, dry, shrink, and sun-crack. The angular blocks of this mosaic may again be covered with water and imbedded in the sediments which it throws down. The conditions for desiccation breccia are afforded where there are long intervals between periodic

[1] C. E. de Rance, *Quar. Jour. Geol. Soc. London*, XLIV (1888), 374.

[2] Jukes, *Manual of Geology* (1886), p. 298.

[3] V. Ball, *Quar. Jour. Geol. Soc. London*, XLIV (1888), 371–74.

[4] Desiccation conglomerates is a term proposed by J. E. Hyde, *Amer. Jour. Sci.*, 4th ser., XXV, 400 f.

floodings, as in the shallow lakes of arid basins and those of river flood-plains and in lagoons cut off from sea except at highest tide or greatest storms. Desiccation breccia may be only as thick as the sun-cracked layer. Where the dried blocks of the mosaic or pieces of their upturned edges are assembled by the waves, the fragments may be irregularly piled in rubble and should show some wear. The matrix differs little from the fragments, and the breccia is endostratic. A special variety is playa breccia. The cracks of the sun-baked clay of the dried-up lake bed may be filled with desert sand, and this accumulates also beneath the curled-up edges of the cakes. Desiccation breccias have been described from the Algonkian of Idaho by Ransome and Calkins,[1] and designated as "mud breccias." The angular or slightly rounded fragments are of argillite and are imbedded in a somewhat coarser-grained and more arenaceous matrix. Sun-cracks are found in direct connection, and the angular fragments are supposed to be broken off from the edges of flakes of mud curled up by drying in the sun.

Volcanic subaqueous breccia.—Volcanic breccia deposited under water may be distinguished from that laid on land by the sediments on which it rests and by the bedding of the tuff. Subaqueous tuff breccias, as remarked by Leith,[2] are distinguished only with very great difficulty from water-laid clastics resulting from the erosion of volcanic rocks.

Shoal breccia.—In this class of submarine breccias, and in reef and beach breccias as well, disruption and assemblage both are caused by waves and tides. The normal action of these agents is to round and sort the coarser stuff they handle and to deposit it in well-defined conglomerates. It is only under exceptional conditions that they can assemble beds of fragments so little worn as to constitute a breccia.

Shoal breccia is formed by the action of waves and tides on shoals due to diastrophic movements or to general aggradation. In reef breccia, on the other hand, there is proof that the shallows permitting wave-pluck are due to local upbuilding of the sea-floor.

[1] F. L. Ransome and F. G. Calkins, "Geology and Ore Deposits of the Cœur d'Alene District, Idaho," *U.S. Geol. Surv., Prof. Paper 62*, p. 31.

[2] C. K. Leith, *Structural Geology* (New York, 1913), p. 66.

Shoal breccias are commonly of limestone. Calcareous sediments rapidly harden by cementation, and may be broken into breccia by waves which under identical conditions merely redistribute the grains and particles of unindurated sands and clays. On shoals of calcareous sediments lying partly above and partly below the plane of effective wave-erosion, waves and tides tear up the cemented beds of the elevations and deposit fragments in the hollows safe from further wear.

In the case of the extensive sheets of brecciated limestone of the Galena and the Niagara formations of Wisconsin, Chamberlin[1] has suggested that the tide may have played an important rôle. Under a large tidal oscillation storm waves may be brought at low tide within reach of the surface of shoals which, except at this brief interval, remains below wave-base. Fragments torn at low tide by storm waves, and the finer waste stirred into suspension, thus have time to settle back together as fragments and matrix of a breccia, and, it may be added, to be further protected by a cover of other sediments before a low tide again coincides with a heavy storm and the process is repeated.

Strong tides working on shoals are postulated by Lane[2] in explaining the limestone breccias of the Salina and Lower Helderberg of Ohio. The prevalence of ripple-marks, mud-cracks, brecciated and conglomeratic layers, leads to the inference of a great flat which seems to have been just awash. "If we imagine tides like those of the Bay of Fundy rushing over this flat, producing this breccia and conglomerate . . . . we have the conditions of the Helderberg on Monroe deposits."

In explaining the foundations of Mississippian reefs in Yorkshire, England, Tiddeman[3] infers local deformations which here and there brought the sea-floor above wave-base. As a result, shoals were formed of wave-plucked angular and more or less rounded fragments on which colonizing corals and mollusks reared their reefs. In a similar way certain Algonkian breccias of Idaho are explained by Ransome and Calkins.[4] "It is supposed that in the

[1] T. C. Chamberlin, *Geology of Wisconsin*, I (1883), 168–69.

[2] A. C. Lane, *Geol. Surv. of Michigan*, V (1895), Part II, p. 27.

[3] R. H. Tiddeman, cited by Marr, *Quar. Jour. Geol. Soc. London*, LV (1899), 330.

[4] *Op. cit.*, p. 38.

vast mud flats upon which the St. Regis beds were being laid down, the surface was raised up into a low dome of small extent upon which the soft strata were exposed to wave action and fragments were broken away and incorporated with the soft siliceous mud that was then accumulating in the surrounding waters."

Reef breccia.—Reefs with brecciform structures may be built by corals, calcareous algae, and molluscous shells. Coral breccia, the variety most common and most closely studied, is produced in several different ways. As a coral reef is built up toward low-tide level, the interspaces between the masses of growing coral are filled with broken fragments of coral branches and the finer waste of the reef. The coral framework is brittle and is further weakened by boring worms and mollusks; hence the accretion of broken branches goes on below the zone of wave-wear, and the fragments remain angular. After wave-base is reached, accretion proceeds still more rapidly, and now the other rim of the reef, the belt of its most active growth, acts as breakwater and protects the inner portions of the coral fields from the wear of the surf. Thus is formed *reef-rock breccia* or coralline rag, a well-cemented limestone in which masses of coral retain the attitude and position of growth, and to which the varied animal and vegetal life of the reef contributes.

In this reef-rock waves cut the channeled and cavernous rock-bench. The fragments plucked from the bench are swept inland by heavy storms over and beyond the beach of coral sand, and cover large tracts with lichen-blackened fragments, angular to such a degree that both Dana[1] and Sollas[2] have compared them to the rough clinkers of lava which strew the slopes of Mauna Loa and of Etna. Intermixed is wave-worn and wind-blown coral sand, which acts as a matrix, cementing the *breccia of the island rock*. By slow subsidence these deposits may be carried beneath the surface of the sea. The upgrowth of the rim of the reef meanwhile protects them from being worked over by the waves and thus the brecciated stucture is preserved.

A third variety of coral breccia accumulates at the foot of the steep outer face of the reef, where angular fragments torn by waves

[1] J. P. Dana, *Corals and Coral Islands* (New York, 1879), p. 178.

[2] W. J. Sollas, *Age of the Earth* (London, 1905), chapter on Funafuti, p. 108.

from the growing corals of the rim come to rest below wave-base. Such a breccia, at the foot of reefs of Mississippian limestones in Great Britian, has been described by Tiddeman.[1]

The characteristics of coral breccia may be enumerated:

1. Like all wave and tide breccias, coral breccia is either a rubble or a pudding breccia. Crackle and mosiac breccias are not to be expected.

2. The matrix consists of the fine detritus of the reef.

3. Both matrix and fragments are singularly devoid of siliceous and argillaceous impurities. An exception occurs in reefs which receive more or less waste from an adjacent land.

4. Reef-rock breccia may show little or no trace of bedding. In the core of the deep boring of the Funafuti atoll, which passes through this rock to a depth of 1,114 feet, the only stratification found was that due to such irregular accumulation of detrital material as occurs between and around the corals.[2] The numerous Silurian reefs of Wisconsin and Iowa show little or no trace of bedding from top to bottom, while areas occur within them of conglomeratic or brecciated structure.[3] In the case of the wave-driven fragments of the island rock some sorting and bedding with low dips are to be expected, and the talus formed below the reef probably shows rude layers dipping outward at the angle of repose.

5. The fragments of coral breccia show varying amounts of wear. Least worn are fragments of reef rock accumulated below wave-base. The island rock necessarily approaches a conglomerate in the rounding of its constitutent masses. How short a time and distance are needed to destroy the angularity of fragments is seen in a photograph and description by Kent[4] of the result of a single tropical hurricane of a few hours' duration in 1884. A fringing reef was wrecked and its fragments, swept inland, were piled above reach of the highest tides. Massive head-corals were torn up and rolled together like the small pebbles of the beach and ground down to subspherical symmetry.

[1] R. H. Tiddeman, *Rept. British Soc.* (Newcastle-on-Tyne), p. 602.

[2] Judd, quoted by Sollas, *op. cit.*, p. 128.

[3] T. C. Chamberlin, *Geology of Wisconsin*, I, 184; W. H. Norton, *Iowa Geol. Surv.*, IX, 424; XI, 307.

[4] Saville Kent, *Great Barrier Reef of Australia*, pp. 50–52.

6. Coral breccia is intimately associated with stratified deposits of coral mud and sand and pebbles. The reef contains stretches of barren sand within the outer rim. The island is bordered by a beach of sand and shows extensive tracts of sand in the interior. Soundings disclose belts of sand with which the talus of the reef must interfinger. Fine-grained limestones are forming in the lagoon and in deeper offshore waters.

7. Fragments may themselves be brecciform. Complex brecciation occurs especially where fragments of the reef-rock breccia are carried inland to form the island rock.

8. The chief diagnostic of an ancient coral breccia is the presence of the reef proved to be the work of corals by its fossils. Thus the classification of the breccia of the St. Louis formation of southeastern Iowa and adjacent parts of Missouri and Illinois as a coral breccia is held untenable by Bain[1] because of the absence of reef-building corals. On the other hand, brecciated structures connected with coral reefs are not necessarily of coral origin. Associated with the Silurian reefs of Iowa are local breccias unquestionably due to the later deformation of beds of limestone accumulated upon the flanks of the coral mounds.

Beach breccia.—On beaches where wave-action is inefficient and angular blocks are supplied as from sea-cliffs, a deposit of fragments so little worn as to be classed as breccia according to prevailing usage may result under conditions of rapid submergence. In all cases, however, more or less wave-wear will be found upon the fragments, and the deposits, like other subaqueous deposits of both angular and rounded material, should perhaps be termed a breccia-conglomerate.

The St. Louis breccia of southeastern Iowa, classified by Gordon[2] as reef breccia, is considered by Bain[3] a shore formation in which blocks of limestone up to 4 feet in diameter were torn from their beds and buried in sands apparently at the foot of a series of cliffs. Savage[4] also finds evidence of vigorous wave-action and a close

[1] H. F. Bain, *Iowa Geol. Surv.*, V, 150.

[2] C. H. Gordon, "On the Brecciated Character of the St. Louis Limestone," *Am. Naturalist*, XXIV (1890), 305–13; *Jour. Geol.*, III, 289 f.

[3] H. F. Bain, *Iowa Geol. Surv.*, V, 150.

[4] T. E. Savage, *Iowa Geol. Surv.*, XII, 263 f.

proximity of the shore. The subaqueous origin of the breccia is confirmed by Van Tuyl,[1] but only in part. The first period of disturbance was one in which, under violent wave-action, mounds of shoal breccia were produced. The major disturbances, however, are of later date and gave rise to tectonic breccias associated with mashing, folds, and overthrust faults.

Tide-glacier breccia.—Tide glaciers, laying their loads on sea-bottom, give rise to breccias which prove their parentage by faceted and scored pebbles of a considerable variety of rocks and by subjacent disturbed sedimentary deposits or glacier pavements where the ice has overridden the sea-floor. Associated stratified beds with littoral fossils prove the breccia submarine. Icebergs detached from the glacier front extend the formation seaward in an ice-raft breccia, with a lessening proportion of morainal stuff.

The Chaix Hills, described by Russell,[2] are carved from an uptilted block 4,000 or 5,000 feet thick, composed of morainal material and sea-clays. The fragments of this breccia are sporadic throughout the terrane from base to summit. They are both angular and rounded and reach a diameter of some 8 feet. Lithologically they are as various as are the bowlders of the moraines of the living glaciers of the encircling mountains. Sea-shells of living species are numerous in the finer portions, which are largely made of glacier silts.

Glide breccias.—The sediments of the sea-floor are subject to slow and rapid gravitational movements, comprehensively termed glides, which deform, shatter, and brecciate the involved strata. Glides may be expected to affect the steeper slopes, such as the sides of submarine channels, the front of deltas, and the edges of continental shelves. They are known to have taken place on slopes as low as about three degrees. The mobility of marine deposits is increased by permanent saturation and frequently by lack of cementation.

Subaqueous glides may be classified according to their chief precipitory causes as *overload* glides, *earthquake* glides, and *deformation* glides.

[1] F. M. Van Tuyl, "Brecciation Effects in the St. Louis Limestone," *Bull. Geol. Soc. Am.*, XXVII, 122–24.

[2] I. C. Russell, "Second Expedition to Mt. St. Elias," *U.S. Geol. Surv., 13th Ann. Rept.*, pp. 24–26.

Overload glides: On land, gravitational movements occur on slopes due chiefly to erosion; on the sea-floor unstable equilibrium must often result from aggradation. Sediments are unequally spread owing to set of current and distance from sources of supply. Deltas and banks are thus built up, until along their edges overload gives rise to facial shear and glide.

Earthquake glides: The chief geologic effect of earthquakes on land is to precipitate movements both of the waste mantle and of the solid rock beneath. Alluvium on valley floors lurches toward the thalweg, the waste on hillsides, slumps and avalanches, and even solid rock may be intimately shattered and shaken down in landslides of the first magnitude.[1] The effects of earthquakes on marine deposits must be of similar nature and proportionally great. Evidence collected by Milne[2] proves conclusively the fact of subaqueous glides and their close connection in a number of instances with earthquakes. Since the continental delta throughout geologic time has been the zone, not only of sedimentation, but also of great diastrophic movements of which earthquakes are an expression, it may be assumed that earthquakes have been a not uncommon cause of glides in geologic history. Yet no instance is known to the writer in which a glide breccia has been assigned to this precipitory cause. The most direct evidence pointing to such an origin is to be found in contemporaneous associated faults or sandstone dikes. Since earthquakes recur in the same area for long periods of time, earthquake-glide breccias may recur at successive horizons in a formation on in a sequence of formations.

Deformation glides: There is some reason to believe that within the continental delta deformation may so accent the slope that glides of unindurated sediments result. In explaining the Devonian breccia of Iowa, McGee[3] offered as "a useful even though a far-fetched hypothesis" that of an elevation at the close of the Devonian by which the declivity was increased, a consequent slight

[1] *The California Earthquake of April 18, 1906*, I, Part II, pp. 384 f. (Carnegie Institute, 1908); Darwin, *Voyage of a Naturalist* (London, 1891), p. 220; Whymper, *Travels amongst the Great Andes*, IV (London, 1892), 260; Whitman Cross, "Geology of the Rico Mountains, Colorado," *U.S. Geol. Surv., 21st Ann. Rept.*, Part II, p. 149.

[2] John Milne, "Suboceanic Changes," *Geog. Jour.*, X, 129–46, 259–85.

[3] W. J. McGee, "Pleistocene History of Northeastern Iowa," *U.S. Geol. Surv., 11th Ann. Rept.*, p. 323.

settling seaward of the fresh-formed Devonian sediments upon the sloping flanks of the Island of Wisconsin, and a slipping of the strata upon one another causing crumpling, buckling, and brecciation. The same cause is assigned by Hershey[1] for a very local breccia near Galena, Missouri. Minor causes of subaqueous glides are erosion and undercut of submarine banks by springs and currents.

The characteristics of glide breccias are due to the deformation, to the shear and crush of the gravitative movement, and not to its precipitory cause. Hence all the varieties mentioned are alike in structure and have a close resemblance to endolithic breccias caused by deformation.

The fragments are contributed by any layers hard enough to suffer fracture. They may be sharply angular or somewhat worn by mutual attrition. They may be apposed in crackle and mosaic breccias, or disposed in rubble, according to the amount of movement. Fragments may show by their relative positions the initial attitude of the layer before fragmentation. These breccias are likely to graduate into folded structures with parallel and thickened axes and common dips, and the fragments of beds bent before breaking may show flexures and contorted laminae. A zonal arrangement is to be looked for where strata differing lithologically and of a considerable thickness are involved.

The matrix is supplied by the least indurated or most readily comminuted beds, especially by the surface sediments as yet unconsolidated, and by any bottom layer which by its plasticity determines the base plane of the glide. Thus shales furnish matrix to fragments broken from brittle limestones. Matrices evidently pasty and fragments somewhat plastic at time of brecciation point to subaqueous brecciation either by glide or by wave-action, and the former alternative is to be chosen when there are proofs of folding before fracture. This test applies only when brecciation in the zone of flow and fracture is precluded. The relative amount of matrix and fragments is determined by the volumes of strong rock and weak rock involved and by the violence of the movement. Even a breccia of sporadic fragments may result.

[1] O. H. Hershey, "A Devonian Limestone Breccia in Southwestern Missouri," *Science*, N.S., I, 676–78.

Overlying beds are undeformed or share only in later deformations affecting the entire body of the strata. Their contact is accordant where the breccia has been reworked and leveled by wave-action. In this case they contain at bottom fragments of the broken beds, either rounded to a conglomerate or partially angular and forming a pudding or rubble breccia. If the slidden mass is reassembled below wave-base the contact is discordant and superincumbent beds are free from fragments. The breccia may thus be either endostratic or have the hummocky upper surface of a landslide. Glide breccias may graduate laterally as well as vertically into sedimentary beds. They rest on undisturbed strata of earlier date. Endostratic breccias passing within the limits of the same stratum into folded laminae point strongly to an origin in glide. A complete section of a glide and the associated strata would show, according to Heim,[1] the following relations: in the area bared by the glide, (1) a reduction of the number of strata as compared with the adjacent areas, (2) local disconformity without time interval; in the area on which the glided mass came to rest, (3) increase in the number of strata, (4) superposition of older on younger beds, (5) displacement of facies. Glides involving subaqueous and subaërial sediments have occurred in a number of instances on the shores of the Swiss lakes, in Sweden, and along the Black Sea.[2] In the lower Devonian limestones of Gaspe a bed has been described by Logan[3] whose structure is evidently due to subaqueous glide. This bed, 7 feet thick, is made up of several thin layers of limestone and limy shale, wrinkled, contorted, and in places brecciated, while the associated beds are free from marks of deformation.

The edgewise position of broad, flat pebbles in evenly bedded strata near Bellefonte, Pennsylvania, has been attributed by Brown[4] to aqueous glide.

Endolithic breccias.—Of breccias formed within the lithosphere the following classes may be distinguished: (1) tectonic breccia (dynamic, pressure, friction breccia), due to crustal movements

[1] Quoted by A. W. Grabau, *Principles of Stratigraphy* (New York, 191[illegible]), p. 660.

[2] Grabau, *op. cit.*, pp. 657 f., 779 f.

[3] Sir W. Logan, *Geology of Canada* (1863), pp. 391 f.

[4] T. C. Brown, *Jour. Geol.*, XXI, 241–42.

and produced by lateral or vertical pressure or by tension; (2) expansion breccia (caused by increase of volume due to chemical change); (3) founder breccia (ablation, solution breccia), due to the foundering of strata, usually because of the ablation by solution of the supporting beds.

Tectonic breccia.—Three varieties are discriminated: fault breccia, fold breccia, and crush breccia. In the latter, brecciation is accomplished without either faulting or folding except so far as the rupture planes of the breccia may be considered as minute faults.

Fault breccia: Here fragmentation is due either to friction along the fault plane or to distributive ruptures associated with the major fault, and due to shearing stresses. In stratified rock, fault breccias associated with both normal and reversed faults are easily recognized, since the zone of brecciation crosses the planes of bedding. Friction breccias along bedding faults are more difficult to distinguish. Here one must seek for proofs of lateral displacement in slickensides with polish, scorings, and seams of "gouge" (clays formed by grinding). Local breccias of this variety have been identified by Ransome[1] in the Rico Mountains of Colorado.

Complex brecciation is not uncommon, since repeated movements along the fault plane shatter and drag a breccia already formed and firmly cemented with perhaps vein stuff and ore. Breccia zones running parallel with the main fault may show but slight displacement. Thus in the San Francisco district of Utah such breccia zones in brittle quartzite pass downward into monoclinal folds in shale.[2] The rocks on opposite sides of a fault plane may be differently affected—granite, for example, may be sheared and the limestone opposite brecciated.[3] Fault breccias often form aquifers for mineralized waters which deposit matrices of ore and gangue. Many breccias of this class have been brought to notice because of their economic importance.

[1] F. L. Ransome, "Ore Deposits of the Rico Mountains, Colorado," *U.S. Geol. Surv., 22d Ann. Rept.*, Part II, p. 297.

[2] B. S. Butler, "Geology and Ore Deposits of the San Francisco, etc., Districts, Utah," *U.S. Geol. Surv., Prof. Paper 80*, p. 72.

[3] W. H. Emmons and F. C. Calkins, "Geology and Ore Deposits of the Phillipsburg Quadrangle, Montana," *U.S. Geol. Surv., Prof. Paper 75*, p. 151.

Fold breccia: Under suitable conditions of load and stress beds may fold by means of minor fractures. Cross and parallel fracture planes develop, and under increasing stress the fragments are rotated and displaced. The folded bedding is more or less completely destroyed and there results a mosaic or even a rubble breccia. Where the rock is compressed joints or fissility ruptures are produced. A rising anticline develops radial tension cracks along the convex surface as soon as the deformation passes the limit of elasticity of the rock. In the experiments of Willis[1] the first fractures of the arching strata occurred at points of sharpest curvature—along the axial plane at the summit of the anticline and on radial planes of shear at its base. A basal weak stratum, compelled to rise beneath a competent stratum as the latter was bent upward, accommodated itself to the change by shear, resulting in complete brecciation.[2] Here the breccia occupied the center and base of the anticline, while the competent upper beds remained at first unbroken and later under increased pressure were ruptured by a stretch thrust fault.

The degree of folding necessary for brecciation varies with the rigidity of the stratum, with load, and with the amount and rapidity of application of the stress. Even limestone and granite under slight load yield plastically and bend to a perceptible degree when the stress is very slowly applied.[3] On the other hand, brittle rock under presumably sudden stresses breaks into breccia when the deformation has not exceeded a gentle warping.[4] Under the same strain and load different rocks fold or break according to their elasticity. Among sedimentaries the most brittle and therefore the most liable to brecciate are cherts, some shales, and calcilutites; among metamorphic rocks, quartzites, graywackes, and rather siliceous slates. A thin layer of chert may be seen broken into a string of angular bits within a layer of limestone which shows no

[1] Bailey Willis, "Mechanics of Appalachian Structure," *U.S. Geol. Surv., 13th Ann. Rept.*, Pls. 75, 76.

[2] *Ibid.*, Pl. 93.

[3] Arthur Winslow, *Am. Jour. Sci.*, 3d ser., XLIII, 133–34; H. F. Bain, *Iowa Geol. Surv.*, VIII, 378.

[4] Smith and Siebenthal, *U.S. Geol. Surv., Geol. Atlas*, Joplin Folio, p. 9.

other trace of yielding. In the breccias of the Wapsipinicon stage of the Iowa Devonian, a thick, tough, crystalline-granular coquina is normally broken into large slickensided blocks which retain something of the flexures into which the bed was thrown, while subjacent thinly laminated calcilutites are shattered to a jumble of small fragments.[1]

Shales yield plastically under load, but when near the surface and under sudden stress they easily crush to breccia. Shales promote the fragmentation of inclosing and especially of included beds of other rocks. Thus the Wapsipinicon breccias of Iowa embrace the Independence shale and its associated limestones. In the zone of fracture and flowage, alternate thick layers of brittle and of plastic rock may produce brecciated beds, alternating with folded layers, whose arches may be truncated by the movement of the fragments of the rigid and brecciated beds.[2]

Unlike glide breccias, breccias due to folding are included between strata which have shared the brecciating deformation according to their competency. But since any sort of breccia may be involved along with the associated terranes in a later deformation further proof of origin must be looked for in the remains of initial folded structures in the breccia. A certain continuity may be traced from fragment to fragment, showing clearly that the fragments are constituent parts of a flexed and broken layer. The breccia may graduate into folds. Where the breccia involves beds of different kinds of rocks, anticlines and synclines may sometimes be traced in a zonal arrangement of the crushed material.[3]

Crush breccias: The sheet breccias of the Joplin district, Missouri, illustrate how terranes of brittle rock may be brecciated by lateral pressure without any further mass deformation than that exhibited in gentle warpings. Heavy ledges of chert have been thoroughly and finely crushed in places and cemented by a chemical deposit from ground-water. The fragments are of small size and are thus in direct contrast with the residual breccias of a higher

[1] W. H. Norton, *Iowa Geol. Surv.*, IV, 158–61.

[2] C. R. Van Hise, "Principles of North American Pre-Cambrian Geology," *U.S. Geol Surv., 16th Ann. Rept.*, Part I, p. 681.

[3] W. H. Norton, *Iowa Geol. Surv.*, IV, 165.

horizon in the same area. The breccia is endostratic and often of the crackle or mosaic type, with fragments rotated but slightly in the ledge.[1]

In all tectonic breccias the fragments are left of sharpest edge at time of breaking, and a universal sharp angularity points strongly to a tectonic or to other endolithic origin. Yet the fragments may be worn by grinding one upon another in the zone of shear and thus become so completely rounded as to be readily mistaken for the pebbles of a wave-laid conglomerate. Thus are produced the "pseudo-conglomerates" of Van Hise.[2] The rounding of pebbles of a conglomerate, however, is pretty uniform for pebbles of any given size, the smaller being better rounded than the larger. Moreover, the conglomerate graduates into finer sedimentary deposits. The rounding of the fragments of a pseudo-conglomerate is fairly uniform for any given portion of the brecciated zone. Tracts where fragments are well rounded regardless of size pass into tracts where all the fragments are angular.[3] Dale[4] has noted that angular pebbles of soluble rock in an insoluble matrix may be later rounded by the dissolving action of acid ground-water. It may be added that by solution under pressure fragments develop salients and re-entrants, wholly different from either fracture planes or rounding by attrition or solution. Fragments may also show in flexed and contorted laminae evidence of the strain to which their layers were subjected. Such distortion phenomena imply considerable plasticity in the layers, although it was finally exceeded by the strain. Contorted laminae may also be seen in the fragments of breccias originating in subaqueous glides, where the plasticity of the sediment is due to imperfect lithification.

The form and size of the fragments of tectonic breccias so far as due to fracture depend on the amount of stress, the closeness of joints and bedding planes, and the natural fracture of the rock. Thus in one of the experiments of Willis[5] fault planes divided a

[1] Smith and Siebenthal, *U. S. Geol. Surv., Geol. Atlas*, Joplin Folio, p. 9.

[2] Van Hise, *op. cit.*, p. 679. [3] *Ibid.*, p. 680.

[4] T. N. Dale, "Structural Details in the Green Mountain Region," *U.S. Geol. Surv., 16th Ann. Rept.*, Part I, p. 569.

[5] *Op. cit.*, Pl. 93.

brecciating layer at first into rhombs bounded by two faults and two bedding planes, and afterward, under increasing pressure, into triangular forms bounded by two faults and one bedding plane. From brittle, thin-layered rocks under slight stresses quadrangular and subquadrangular small fragments are derived. The sharpest edges are found in rocks of conchoidal fracture, minutely faulted into triangular fragments.

The matrix when contemporaneous is supplied by the material of the weaker beds involved and by wear and tear of the stronger beds. It graduates from powder and angular sand, the product of attrition, to chinkstone, approaching the size of the smaller fragments. When the interstices are left at time of brecciation more or less unfilled, as is likely to be the case, a veinstone matrix of travertine, of jasperoid, or of iron compounds is often deposited later by ground-water. Such a matrix weighs against any origin, e.g., subaqueous glide, which is not likely to leave unfilled interstices. The significance of both veinstone and attrition matrices lies also in the proof they offer that sedimentary deposits had no access to the zone of brecciation.

The material of tectonic breccias, with the exception of the matrix of chemical deposit, derives from the geologic formations of the beds involved. Fragments of beds belonging stratigraphically below the base of the breccia cannot be included in it. On the other hand, in subaqueous or subaërial breccias fragments deriving, for example, from cliffs of Archean rock may be deposited as Devonian breccia on Devonian lands or in Devonian seas. But while in subaërial and subaqueous breccias the matrix is never older than the fragments, in tectonic breccias an older and weaker terrane may supply the attrition matrix, in which the fragments of a younger superjacent stratum are imbedded. Where beds of different rocks are involved zonal arrangement is sometimes traceable, which at once excludes the breccia from many varieties of subaqueous and subaërial origin. A tectonic breccia does not rest, like subaërial breccias, upon an erosion surface. It cannot graduate upward into strata inclosing sporadic fragments. An important diagnostic may be found in undisturbed areas, perhaps of very large size, which have transmitted the strain instead of yielding to it by fragmentation.

Expansion breccia.—Fragmentation may be caused by increase of bulk of the brecciating rock or of associated layers which transmit the pressure to it. Expansion may be caused by recrystallization or by hydration. Expansion breccias graduate into folded structures, but the folds show quaquaversal deformation, the *enterolithic* structure of Grabau,[1] a term translating the "Gekröse" of Koken, and this intestinal coiling may serve to distinguish them and the associated breccias from folds and breccias due to lateral pressure.

Founder breccia.—Where beds of soluble rocks have been in part or whole removed by the chemical action of ground-water, founder breccias of the superincumbent beds are produced on a scale commensurate with the extent of the ablation. All terranes between the dissolving foundation and the surface of the ground or some competent superior stratum are affected by the process. Characteristic features are abnormal dips, sag folds without parallelism of axes, areas of crushed rock alternating with horsts where the strata are undisturbed. The matrix may be of crushed material of the same terrane as the fragments. In this case it is likely to be small in amount and insufficient to cement the breccia firmly, for the attrition of the fragments in founder is probably much less than in tectonic brecciation. The matrix may be a later chemical deposit.

The fragments show only the small wear due to mutual attrition. Like other endolithic breccias, a founder breccia can carry no water-worn pebbles. It is conceived that founder breccias of thick extensive beds include larger blocks than any other type of breccia excepting that due to landslide. Certainly they may be far too great for detachment by waves or by mechanical weathering and for fragmentation under lateral pressure. Horsts may be difficult to discriminate from the undisturbed areas of tectonic breccias.

Thin-shale founder breccias have been described by Ransome[2] in the blankets of several mines in the Rico district, Colorado. The blanket of the Enterprise mine, for example, is an unconsolidated breccia of shale from 2 to 20 feet thick, resting on a thin

[1] *Principles of Stratigraphy*, p. 757.

[2] F. L. Ransome, "Ore Deposits of the Rico Mountains, Colorado," *U.S. Geol. Surv., 22d Ann. Rept.*, Part II, p. 273 f.

bed of light-gray earth, shown by chemical analysis to be a residuum of gypsum.

The Monroe breccia of Michigan is considered by Hindshaw[1] to be of this type, although Lane[2] has classified it as a shoal breccia and Grabau[3] as a rock-stream or rock-glacier breccia, at least in its outcrops at Mackinac Island and the vicinity. As observed by the writer, the breccia at this locality is a rubble, entirely without bedding, of angular fragments set at all angles and varying in size from gravel up to blocks 25 and 30 feet in length. Fragments and matrix are of soft buff magnesian limestone, and the latter is usually interstitial. Occasional seams of calcite and celestite occur. In certain areas a zonal arrangement of material is seen in the prevalence of chert, showing that the material of the breccia has not been intimately mingled as in subaërial breccias whose fragmentation is due to weathering. A still more conclusive negative to such an origin is given in areas of rock quite undisturbed, such as a block extending eastward along the cliffs for upward of 200 feet from the eastern border of the park at Mackinac. This observation is confirmed by Rominger,[4] who states that "frequently large rock-masses composed of a series of successive ledges which have retained their original position to each other are scattered through the breccia." The wide distribution of the breccia in Michigan and Ohio precludes any local origin. The size of the fragments and the absence of water-wear are considered inconsistent with a subaqueous origin. Along the eastern shore of the island, however, numerous talus blocks show endostratic brecciation. Laminae flexed and faulted and partially brecciated are imbedded in a matrix of the same material and maintain more or less of their original parallelism with each other and with the bedding of the stratum. In the undisturbed block at the east of the park at Mackinac sporadic fragments occur toward the base of massive beds. These phenomena imply disturbed sedimentation, or sub-

[1] *Michigan Geol. and Biol. Surv. Publ. 14*, Geol. Ser. 11, pp. 206–7.

[2] A. C. Lane, *Geol. Surv. Michigan*, V, Part II, p. 27.

[3] A. W. Grabau, *Science*, N.S., XXV, 295–96; *Principles of Stratigraphy*, pp. 547–48.

[4] Carl Rominger, *Geol. Surv. Michigan*, I, Part VI, p. 27.

aqueous glides, at the time of the deposit of the limestone, but the main brecciation is taken to be of later date.

There is also seen an association with folds which suggests either a tectonic or a founder breccia. The underlying red and blue shales seen in the rock bench about the island rise in places as anticlines in the sea-cliffs. On the cliffs east of the fort at Mackinac, beneath a cornice of about 15 feet of horizontal massive beds, appears a zone, 9 feet thick, of thin-bedded limestone, thoroughly crackled, with unhealed seams, shattered, and in places with the fragments rotated and displaced, but with the bedding still traceable to a large extent. In places low folds can be made out with a height of 8 inches and width of some 4 feet, a deformation apparently adequate to brecciate this brittle rock.

The theory of founder presupposes the removal by solution of beds of rock salt and gypsum underlying the red and blue shales on which the limestone rests. These shales are not commingled with the breccia of the limestone. If the breccia is due to founder, it must be concluded that the soft clay shale yielded plastically to unsupported pressure of overlying beds without mixing with the fragments into which these beds were broken. In places small chimneys of breccia penetrate the shales beneath, and the ledges of breccia which rise in reefs above the country rock of shale in the low ground of the north of the island may have a like relation.

The grounds on which Hindshaw's theory of founder is supported are as follows:[1] The Monroe formation rests on the Salina, which includes beds of salt, in places 800 feet in thickness, and of anhydrite partially changed to gypsum. The Monroe itself contains beds of anhydrite. In the Monroe beds and in the overlying Dundee limestone, which is also involved in the brecciation, the circulation of ground-water is exceptionally active. Discordant and abnormal dips occur, accountable for by slumping due to solution of the Salina beds about their outer edges.

Cavern breccia is a local variety of founder breccia. Detached masses fall from the roof and sides of a cave and accumulate on the floor as breccia, which may come to fill nearly the entire space. Cavern breccias may sometimes be recognized by their shape as

[1] *Op. cit.*, pp. 206–7.

casts of the irregular chambers and chimneys of caverns whose walls remain as molds. Cave earth, bone breccia, incorporated fragments of stalactites, and stalagmitic crusts may certify the origin. The matrix is either of travertine or of limestone sand and cave earth.

Campbell[1] has described a cavern breccia exposed in the walls of a canyon near Fort Stanton, New Mexico, and suggests that the frequent repetition of the process might result in complete brecciation of certain beds more soluble than the rocks above and below.

Cavern breccias are common in the lead and zinc mining regions of the Upper Mississippi Valley. Fragments of sheets of ore mingle with the dolomite débris. The matrix may be metalliferous, giving rise to sprangle ores. Slight foundering of the strata above caverns has produced crackle breccias whose fissures are healed with Smithsonite.[2]

Pseudo-brecciation.—This term is used by Wallace[3] to designate irregular mottlings due to partial dolomitization. Various other causes produce irregular mottlings, but such can hardly be mistaken for brecciation structures.

[1] M. R. Campbell, "Origin of Limestone Breccias," *Science*, N.S., XXVII, 348.

[2] Whitney, *Geology of Iowa*, I, 448; A. C. Leonard, *Iowa Geol Surv.*, VI, 11 f.; S. Calvin and H. F. Bain, *ibid.*, X, 480 f.

[3] R. C. Wallace, *Jour. Geol.*, XXI, 420–21.

Reviews

Stratigraphy of the Pennsylvanian Series in Missouri. By Henry Hinds and F. C. Greene. Missouri Bureau of Geol. and Mines, Vol. XIII, 1915. Pp. 407, figs. 5, pls. 32, map 1.

This volume treats chiefly of the stratigraphy, paleontology, and lithology of the barren formations of the Pennsylvanian series in this state, thus supplementing Vol. XI, which deals primarily with the coal deposits.

The subdivisions now recognized in the series are given below:

Group	Formation
Missouri	Wabaunsee Shawnee Douglas Lansing Kansas City
Des Moines	Pleasonton (unconformity in) Henrietta Cherokee

The formations in this classification are differentiated into 30 members which might be called formations by those who give the Pennsylvanian the rank of a system. The system is markedly unconformable on the beds beneath, and its upper members are the youngest consolidated rocks in the state.

The Des Moines and Missouri groups were differentiated originally with the belief that the latter contained much greater quantities of limestone. The only basis now recognized is a rather well-marked faunal break. There are rather strong indications of a widespread unconformity in the Pleasonton, and this faunal break may be related to it. If this is found to be true the plane between the two groups will be drawn at the unconformity. There has been much confusion in the nomenclature of the Pennsylvanian of this area owing to duplication of names and miscorrelations. That considerable progress has been

made in correcting this situation is indicated by the fact that the classification of this report has been approved by the United States Geological Survey and is now official for the state surveys of Kansas, Iowa, and Nebraska with one minor exception in each of the last two states.

Lithologically, the series is made up chiefly of shales alternating with limestones. Sandstones, clay, and coal are found in lesser quantities. Most of the lithologic units are quite persistent laterally, but a few are notably lenticular. The broader features of the present structure have resulted from two periods of folding since the close of the Pennsylvanian. The first of these developed monoclinal dips to the west and northwest and the second formed a number of narrow anticlines with associated synclines. The axes of these folds are markedly parallel and trend northwest-southeast throughout the state. These are shown on a structure contour map drawn on the basis of rather meager data.

Invertebrate paleontology is the subject of an exhaustive chapter by Dr. Girty. More than 250 collections containing more than 350 species form the basis of his report. The species are listed by localities and by zones for each formation, and the valuable data of these lists is made available more readily by a composite table showing the range of each species. Descriptions and illustrations are given of a number of species that are new or have been called into question. Paleobotany is discussed in a short chapter by David White.

Some progress has been made in correlating the Missouri series with eastern areas. Paleontological evidence indicates that the lower part of the Cherokee is of Pottsville age and the upper part is basal Allegheny. It is suggested on the basis of incomplete collections that Allegheny time extends to the unconformity in the Pleasonton and that Conemaugh time ends well up in the Shawnee.

The writers of this valuable report did not fail to include a chapter of bibliography which includes all the important publications consulted in its preparation.

W. B. W.

The Red Iron Ores of East Tennessee. By ERNEST F. BURCHARD. Bull. Tenn. Geol. Survey No. 16, 1913. Pp. 173, pls. 17 (including 5 maps), figs. 30 (including 6 maps).

The purpose of this report is to describe and explain the origin of the red iron ores as they occur in the Cumberland Plateau and the Great Valley in east Tennessee.

It is not possible to give a generalized section of the strata in east Tennessee because of the local variations in the sequence. The ores are contained chiefly in the "Rockwood" formation (Silurian). They are found also in the Tellico sandstone (Ordovician) and to a very minor extent in the Grainger shale (Devonian and Mississippian). Two widespread formations, the Knox dolomite (Cambrian and Ordovician) and the Chickamauga limestone (Ordovician), occur below the Tellico and "Redwood." The Chattanooga shale (Devonian) and the Newman limestone (Mississippian) which lie above the "Rockwood" are important, the former as a reference horizon for the "Rockwood" ore and the latter as a source of the limestone for fluxing material in the iron industry.

In general the beds of the Cumberland Plateau are nearly horizontal, while those of the Great Valley are tilted, folded, and faulted.

The term iron ore as used in this report includes that which runs 20 or more per cent metallic iron. The red ores consist essentially of hematite; the impurities are calcium carbonate, silica, alumina, magnesium carbonate, sulphur, phosphorus, and manganese.

The Tellico ore varies from a ferruginous sandstone to lenses of compact rich ore. The deposits near Riceville, near Sweetwater, and east of Knoxville (here the ore is dominantly limonite) are described; the two last mentioned are residual deposits.

The "Rockwood" formation is composed of lenses of sandstone, shale, limestone, and hematite; its thickness varies from a few feet to over 1,000 feet. The ore beds are mainly in the upper 60–200 feet. The ore is "a mixture of fossil fragments and flaxseed-shaped grains." The soft ore (due to the leaching of calcium carbonite from hard ore) carries 40 to 58 per cent metallic iron, while the hard ore runs from 25 to 45 per cent metallic iron. It is believed "that the 'Rockwood' iron ore was formed by the deposition in a body of water of sediments containing iron, together with calcium carbonate, silica, alumina, and other minerals in minor proportions." Later much of the calcium carbonate of the fossils was replaced by iron oxide; this may have occurred even before the consolidation of the strata and "it probably involved only the original sediments." The "Rockwood" ore outcrops more or less continuously along the base of the Cumberland escarpment and in the Tennessee Valley; the total linear exposure, if only a single seam is taken into account, is 245 miles, of which 60 miles is workable hard ore.

Central east Tennessee is the most productive area in the state.

Underground (slope and adit) mining is carried on almost exclusively.

"Notes on the Iron Industry" conclude the report.

V. O. T.

Geology and Coal Resources of North Park, Colorado. By A. L. BEEKLY. U.S. Geol. Survey, Bull. 596, 1915. Pp. 118, pls. 12.

North Park is described as a synclinal basin limited on the east and west by anticlinal mountain ranges, on the south by a high ridge composed of Tertiary extrusives, and on the north by an area of pre-Cambrian crystalline rocks faulted up into contact with the Paleozoic and later sediments of the Park. The latter comprise two sharply distinct groups: the lower, which rests upon pre-Cambrian crystallines, begins with a few feet of limestone of doubtful age, at the base of the Red Beds, and ends with the Pierre shale—7,400 feet of beds in all, apparently conformable throughout; the upper group comprises some 5,000 feet of uppermost Cretaceous or Eocene strata included in the Coalmont formation. The folding of the region took place in part prior to the deposition of the Coalmont and in part later. Moderately extensive faulting accompanied or followed the later folding, and therefore affected the Coalmont in common with the older rocks. Lying upon the Coalmont in uncertain relationship is the North Park formation, a 600-foot series of clastic sediments interbedded with sheets of pyroclastic volcanics. The Tertiary igneous rocks near the southern border of North Park occur in both intrusive and extrusive relations. Andesine basalt and volcanic agglomerate are the chief types. Granite is the chief constituent of the pre-Cambrian complex exposed in the mountains east, west, and north of the Park.

Coal occurring in the lower part of the Coalmont formation is the one mineral resource of this area which is now being exploited. More than two billion tons of sub-bituminous coal are estimated as the available reserve. The coal seams are of unusual thickness, one bed reaching a thickness of more than 50 feet, and maintaining an average thickness of 30 feet along a 15-mile outcrop.

C. W. T.

Common Minerals and Rocks: Their Occurrence and Uses. By R. D. GEORGE. Bull. Colo. State Geol. Survey No. 6, 1913. Pp. 406, pls. 5.

The main purpose of this bulletin is to describe the commoner minerals and rocks, and furnish the means of recognizing them and knowing their uses.

V. O. T.

The Iditarod-Ruby Region, Alaska. By HENRY M. EAKIN. Bull. U.S. Geol. Surv. No. 578, 1914. Pp. 45, pls. 6 (including 4 maps), fig. 1.

The Iditarod-Ruby region is situated in west-central Alaska between the headwaters of the Iditarod and the Yukon at Ruby.

The geologic succession is as follows: probable Paleozoic metamorphic rocks; Cretaceous sedimentary and volcanic rocks; post-Cretaceous intrusives; Quaternary unconsolidated deposits that include glacial material.

Conglomerates (in places several hundred feet thick), the material of which has been derived from the underlying metamorphic rocks, occur principally near the base of the Cretaceous beds. Some contain bowlders up to 3 feet in diameter.

Placer gold, with a minor amount of silver, is the mineral resource of the region. The gold has been derived chiefly from quartz veins (which are probably genetically related to the post-Cretaceous intrusions) that traverse the igneous, sedimentary, and metamorphic rocks.

The value of the gold and silver produced in 1912 in the Iditarod, Innoko, and Ruby districts was respectively $3,500,000, $250,000, and $150,000.

In 1913 the value of the winter production in the Ruby district was $102,200, while that of the summer production was estimated at $750,000.

V. O. T.

The San Franciscan Volcanic Field, Arizona. By HENRY HOLLISTER ROBINSON. Professional Paper, U.S. Geol. Survey, No. 76, 1913. Pp. 213, pls. 14 (including 2 maps), figs. 36 (including 8 maps).

The San Franciscan volcanic field embraces an area of about 3,000 square miles in north-central Arizona.

Chap. i is devoted to the geography of the region.

Chap. ii treats chiefly of the sedimentary formations and structure. The sequence of sedimentary rocks is as follows: the Mississippian and Pennsylvanian Redwall limestone; the Pennsylvanian Supai formation ("Lower Aubrey" sandstone and shale), Coconino ("Upper Aubrey") sandstone, and Kaibab ("Upper Aubrey") limestone; the Permian(?) Moencopic formation (red to light-brown shales, with some sandstone and calcareous layers); the Triassic "Lithodendron formation" (basal

conglomerate, sandstone, shales, and "marls") and "Leroux formation" (shales, with some sandstone and calcareous beds); and Quaternary moraines and alluvium. The thickness of this generalized section is about 2,500 feet. An unconformity occurs between the Kaibab and the Moencopic, between the latter and the "Lithodendron formation," and between the Triassic and later rocks. The Moencopic formation is a fluviatile or shallow-water deposit; the Triassic beds are continental deposits. The major structural feature of the region is a very flat anticline which trends N. 30° W.

Chap. iii gives detailed descriptions of the volcanoes and lava fields. Three general periods of volcanic activity are recognized: (1) widespread basaltic eruptions from small cones, (2) eruptions of lavas (andesites to rhyolites) to form a few large cones, and laccolithic intrusions, (3) extrusion of basalt (less widespread but more cones built up than in the first named). San Francisco Mountain, which is the principal feature of the area, is composed of "lavas and breccias belonging to five distinct stages of eruption."

"The Geologic History of the Volcanic Field and Adjacent Country" is given in chap. iv. The volcanic activity of the first period occurred in the late Pliocene after the peneplanation of the region, that of the second period took place in the early Quaternary during or after the mature dissection of the area, and that of the third period during the latter part of the Quaternary subsequent to broad regional uplift. There was folding and flexing during the latter half or at the close of the Eocene. Faulting occurred at the close of the Miocene, at the close of the Pliocene, and during the middle or latter part of the Quaternary.

The last two chapters, v and vi, are devoted respectively to petrography and petrology.

V. O. T.

Transactions of the American Institute of Mining Engineers. Vol. L. New York, 1915. Pp. 1008.

Material for this volume was presented at the Pittsburgh meeting in October, 1914. Three topics include the major portion of the volume: (1) iron, geology, and metallurgy; (2) coal and coke with by-products; and (3) petroleum. The volume contains less purely geological matter than either of the preceding volumes for the year. Fifty-two papers and discussions, many of which are illustrated, are included.

A. D. B.

Triassic Life of the Connecticut Valley. By RICHARD SWANN LULL. Connecticut Geol. and Nat. Hist. Survey, Bull. 24.

The author interprets the environment, both physiographic and climatic, of Newark time in the Connecticut valley, and gives a full discussion of the animal life with descriptions and illustrations of both the fossils and the trails and footprints in these beds.

The remarkable thing about this fossil field is that actual fossils are exceedingly scarce but trails and footprints are found in marvelous abundance. In actual fossils the invertebrates are represented by only two species of *Unio* and a single aquatic insect species. The terrestrial vertebrate skeletons are all reptilian, consisting of only two species of phytosaurs, two of aëtosaurs, and five of theropod dinosaurs.

However, the trails and footprints indicate a much greater and more varied fauna. Of the invertebrates, annelids, insects, spiders, scorpions, and fresh-water crustaceans of great variety were doubtless present. The footprints represent two, possibly three, classes of terrestrial vertebrates—amphibia of salamandrine form and also stegocephalians; among the reptiles, lizards, turtles, and dinosaurs, and possibly, also, rhynchocephalians, phytosaurs, aëtosaurs, and theromorpha. There is no evidence that birds were present.

C. H. E.

The Cretaceous-Eocene Contact in the Atlantic and Gulf Coastal Plain. By L. W. STEPHENSON. Professional Paper, U.S. Geol. Survey, No. 90-J, 1915. "Shorter Contributions to General Geology, 1914." Pp. 155–81, pls. XI–XIX (including 2 maps), figs. 13–20 (including map).

"The Cretaceous deposits of the Atlantic and Gulf Coastal Plain are separated from the overlying Eocene and younger formations by an unconformity of regional extent"; the unconformity can be traced from New Jersey to the Rio Grande, and from there southward into Mexico.

After the Upper Cretaceous sediments were laid down, the sea withdrew to the south and east some distance beyond the present shore-line; the Lower Eocene beds were deposited on a nearly base-leveled surface.

The faunal changes that occurred between the deposition of the uppermost Cretaceous and the lowermost Eocene strata were very profound; out of 168 species representing 89 genera in the *Exogyra costata* zone, which includes the upper part of the Selma chalk (uppermost Cretaceous), 20 or more common genera and practically if not all of the

species became extinct before the Midway group (lowermost Eocene) was deposited. Stephenson quotes T. W. Vaughan as follows: "The changes that took place in the marine animal life of the Atlantic and Gulf Coastal Plain during the time represented by the unconformity separating the Cretaceous and Eocene of this area are more striking than the changes that have taken place between earliest Midway time and the present day. . . . ."

V. O. T.

The Stratigraphy of the Montana Group, with Special Reference to the Position and Age of the Judith River Formation in North-Central Montana. By C. F. BOWEN. Professional Paper, U.S. Geol. Survey, No. 90-I, 1915. "Shorter Contributions to General Geology, 1914." Pp. 95–153, pl. 1.

The area treated in this report "lies east of the Big Snowy and Judith mountains and extends from Musselshell, on Musselshell River, to Judith, on Missouri River, Mont." The generalized section of the sedimentary rocks in ascending order is as follows: *Cretaceous*: Colorado shale (thickness not measured), Montana group (Eagle sandstone) (200–300 feet), Claggett formation (700± feet), Judith River formation (250–500 feet), Bearpaw shale (1,100± feet); and the *Eocene*(?) Lance formation (700–800 feet). There is no evidence of an unconformity at any horizon in this section.

It is concluded that "the evidence of the vertebrate fauna, so far as in the present state of knowledge it has any weight, and the evidence of the fresh- and brackish-water invertebrates, so far as it is decisive for accurate time determination, indicate a closer relationship between the Belly River [of Canada] and Judith River than between either of these formations and the Lance. This is in accord with the stratigraphic evidence, which shows conclusively that both the Judith River and Belly River formations are separated from the Lance by amarine formation which is of undoubted Cretaceous age."

V. O. T.

Statistics of the Mineral Production of Alabama for 1913. By CHARLES A. ABELE. Geol. Surv. of Alabama, Bull. 15. University, 1914. Pp. 67.

A compilation from Mineral Resources of the United States.

A. D. B.

The Coalville Coal Field, Utah. By CARROLL H. WEGEMANN. U.S. Geol. Survey, Bull. 581-E, 1915. Pp. 24, pls. 6.

The Coalville coal field lies about 30 miles northeast of Salt Lake City, in the valley of Weber River. High-grade sub-bituminous coal has been mined here for more than fifty years.

The report covers four townships. The rocks of the district include some 8,000 feet of shales and sandstones of Colorado and Montana (?) age, which are folded into a slightly overturned and pitching anticline, and are unconformably overlain by 1,000 feet or more of Wasatch conglomerate. Several transverse and nearly vertical faults of small displacement cut the gently dipping limb of the fold. Both the folding and the faulting took place chiefly in pre-Wasatch time, when considerable erosion was likewise accomplished; but weaker movement of both types appears to have followed the deposition of the Wasatch beds.

The one productive coal bed, known as the "Wasatch" bed, varies from 5 to 12 feet in thickness. This coal compares favorably in quality with several Wyoming coals. Coal occurs in thinner seams at two other horizons, 2,000 feet above and 850 feet below the "Wasatch" bed, respectively. All three horizons are in the Cretaceous system.

C. W. T.

Preliminary Report on the Clay and Shale Deposits of the Province of Quebec. By J. KEELE. Canada Dept. of Mines, Memoir 64. Ottawa, 1915. Pp. 280+iv, pls. XXXIV, figs. 13, map 1.

Describes the clay-bearing horizons and groups producing localities by the age of the clay produced. Particular emphasis is laid on the Pleistocene clays. A considerable portion of the memoir is devoted to the technologic aspects of the clay industries.

A. D. B.

"The Pebble Phosphates of Florida." By E. H. SELLARDS. *Florida Geol. Survey, Seventh Annual Report,* 1915, pp. 25–116.

In an earlier report this writer has discussed the origin of hard-rock phosphates, and this paper extends the study to land-pebble and river-pebble deposits. The land-pebble phosphates are found in the Bone Valley formation of late Miocene or early Pliocene age. They form a portion of a basal conglomerate laid down by a sea advancing over the Alum Bluff formation, a phosphatic marl of late Oligocene age. In this

marl the phosphate was in the form of pebbles and more finely divided material. As the result of a long period of erosion covering most of the Miocene, the phosphatic materials accumulated at the surface and were reworked by the Bone Valley sea. The river-pebble deposits have been formed in the beds of streams that have lowered their channels into either the Alum Bluff or the Bone Valley phosphate horizons.

W. B. W.

Lewis and Gilmer Counties. By DAVID B. REGER. West Virginia Geol. Survey, 1916. Pp. 660, figs. 12, pls. 30, maps 2.

Several volumes each year are added to the excellent county reports already published by this state. Lewis and Gilmer counties, located near the center of the state, have large coal deposits and are rich in oil and gas. Some of the largest gas wells of the Appalachian field were drilled in Lewis County.

The Pennsylvanian formations do not reach the development in these counties that is reported from areas to the south and west. The Pittsburgh seam of the Monongahela series carries the principal coal reserve, and the oil and gas sands range in age all the way from the Chemung to the Dunkard series.

W. B. W.

The Montana Group of Northwestern Montana. By E. STEBINGER. Professional Paper, U.S. Geol. Survey, No. 90-G, 1914. "Shorter Contributions to General Geology, 1914." Pp. 61–66, fig. 1.

The Montana group of northwestern Montana is composed of four conformable formations which are, in ascending order: the Virgelle sandstone (220 feet thick) which is chiefly marine, the Two Medicine formation (1,950 feet thick) which is mainly a fresh-water deposit, the marine Bearpaw shale (490 feet thick), and the brackish and marine Horsethief sandstone (360 feet thick). These formations are similar to those of the Montana group described in southern Alberta by Dawson, but differ decidedly from those in the central part of Montana. The Belly River series of southern Alberta is equivalent to the Virgelle sandstone plus the Two Medicine formation, and these in turn are equivalent to the Eagle, Claggett, and Judith River formations (of central Montana) combined.

V. O. T.

Supposed Oil-Bearing Areas of South Australia. By ARTHUR WADE. Geol. Survey of South Australia, Bull. 4, 1915. Pp. 54, figs. 12, pls. 3.

This bulletin gives the results of field search for oil-bearing horizons in four areas along the seacoast. The rocks in these areas are largely pre-Cambrian schists and quartzites either outcropping or concealed by a thin covering of Tertiary sediments. On Kangaroo Island are clastics assigned to the Cambrian, and glacial deposits doubtfully Permo-carboniferous in age.

The writer finds nothing in the lithology or structure of the strata that can be interpreted as favorable to oil accumulation. He believes that fragments of asphaltum found along the shore have come from beds down-faulted beneath the sea by the great fractures along the southern edge of the continent.

W. B. W.

Coal Fields of Kittitas County. By E. J. SAUNDERS. Washington Geol. Survey, Bull. 9, Pp. 204, figs. 52, pls. 38.

Kittitas County has led all the counties of this state in the production of coal for many years. The output is chiefly from a 19-foot vein in the Roslyn formation of middle Eocene age. The coal is of good bituminous grade and quite free from impurities. The general structural relations of the beds are quite simple, but there are many striking local exceptions, and some of these are illustrated by an excellent series of photographs and diagrams.

In certain portions of the county the Manastash formation of upper Eocene age carries coal beds that are of no commercial importance at present.

W. B. W.

Contributions to the Stratigraphy of Southwestern Colorado. By WHITMAN CROSS and ESPER S. LARSEN. Professional Paper, U.S. Geol. Survey, No. 90-E, 1914. "Shorter Contributions to General Geology, 1914." Pp. 39–50, pl. 1, figs. 2.

The overlap of the Gunnison formation (= La Plata sandstone (Jurassic) below + McElmo formation (Jurassic[?] (above) on pre-Cambrian rocks "extends at least 50 miles farther up the valleys of the Gunnison and Tomichi than was represented for the Jurassic beds on the Hayden map. . . . . The relations in the Piedra Valley suggest that the La

Plata sandstone overlapped earlier sediments and came into contact with the pre-Cambrian rocks along a general north-and-south line, crossing the San Juan Mountains area." The pre-Dakota section of Piedra Valley is given.

V. O. T.

A Reconnaissance in the Canyon Range, West-Central Utah. By G. F. LOUGHLIN. Professional Paper, U.S. Geol. Survey, No. 90-F, 1914. "Contributions to General Geology, 1914." Pp. 51–66, pl. 1, figs. 4–8 (including map).

The Canyon Range in west-central Utah is formed almost wholly of lower Mississippian and older(?) limestone, and upper Mississippian and Pennsylvanian(?) quartzite, overlain unconformably by Eocene conglomerate. Pleistocene Lake Bonneville beds and, locally, later Quaternary deposits floor the valleys on either side of the range. "Volcanic rocks have been reported from the extreme northern and southwestern parts of the range, beyond the limits of the area visited."

V. O. T.

The History of a Portion of Yampa River, Colorado, and Its Possible Bearing on That of Green River. By E. T. HANCOCK. Professional Paper, U.S. Geol. Survey, No. 90-K, 1915. "Shorter Contributions to General Geology, 1914." Pp. 183–89, pls. 2.

Yampa River, which is one of the principal tributaries of Green River and empties into it from the east, is believed to be a superimposed stream whose present course was established after the deposition and emergence of the Browns Park formation (Eocene?). It is thought that "the assertions of the antecedent origin of Green River should be accepted only after more facts have been obtained bearing on the original extent and thickness of the late Tertiary formations, as well as on the diastrophic history of the Uinta Range."

V. O. T.

"The Gold-Bearing Gravels of Beauce Co., Quebec." By J. B. TYRRELL. *Bull. Am. Inst. Mining Eng.*, 1915, pp. 1–12.

Describes the placer deposits of the Chaudiere, Gilbert, and Des Plantes rivers. A point of physiographic interest is the suggestion of an Appalachian center of glaciation, from which the ice is thought to have moved northwestward over the area included in the report.

A. D. B.

The Manufacture of Gasoline and Benzene-Toluene from Petroleum and Other Hydrocarbons. By W. F. RITTMAN, C. B. DUTTON, and E. W. DEAN. U.S. Bureau of Mines, Bull. 114, Washington, 1916. Pp. 268, figs. 45, pls. 9, tables 83.

Contains the details of the methods employed by Rittman and his associates, with the results obtained on both laboratory and factory scale. The bulletin is of especial importance because it incorporates the results of experimental work that has been given wide publicity by the press.

The demand for the bulletin has been so great that the edition for free distribution was exhausted within a month of the date of its release by the Bureau.

A. D. B.

"An Arrangement of Minerals according to Their Occurrence," By E. T. WHERRY and S. T. GORDON. *Proceedings of the Academy of Natural Sciences of Philadelphia*, August, 1915, pp. 426–57.

The classification is the most comprehensive attempt that has come to the notice of the reviewer, and likewise the most successful. The divisions made are rather too numerous for use in an elementary class, but are of great value to advanced students. Doubtless other divisions could be made, which might be more useful for specific studies, such as a further division of the hydrothermal deposits for studies of ore deposits, but in general the classification is an improvement over former attempts.

A. D. B.

Corundum, Its Occurrence, Distribution, Exploitation and Uses. By A. E. BARLOW. Canada Dept. of Mines, Memoir 57. Pp. 377+vii, pls. xxviii, fig. 1, maps 2.

Corundum-bearing syenites, nephelite syenites, syenite pegmatites, and anorthosites occur in three belts north of Lake Onatario. These rocks are chiefly in the Laurentian gneiss, but are also found cutting the Grenville series. The memoir is devoted to a detailed description of the more important localities, including analyses and petrographic description of the rocks, and to the economic and technologic features of the corundum industry, not only of Canada, but of the industry in various parts of the world.

A. D. B.

Transactions of the American Institute of Mining Engineers, Vol. XLVIII. New York, 1915. Pp. 753.

This volume contains papers and discussions of the New York meeting of February, 1914. It contains papers of interest to mining men, geologists, metallurgists, oil producers, mill operators. The discussion of the general topic of revision of mining law occupies a considerable portion of the volume. More attention is given to the discussion of petroleum than in any previous volume. Of particular interest in this connection are papers by von Hofer and by Coste, presenting diametrically opposed views on the origin of petroleum. These, with the discussion they brought out, are worthy of the attention of anyone interested in the geology of petroleum deposits.

A. D. B.

Transactions of the American Institute of Mining Engineers. Vol. XLIX. New York, 1915. Pp. 853.

Contains papers and discussions of the Salt Lake City meeting of August, 1914. The greater number of papers bear on mining, milling, and metallurgy, especially on the leaching of copper ores and the methods of precipitation of copper from the solutions obtained. Forty-nine titles are included. Many of the papers are illustrated.

A. D. B.